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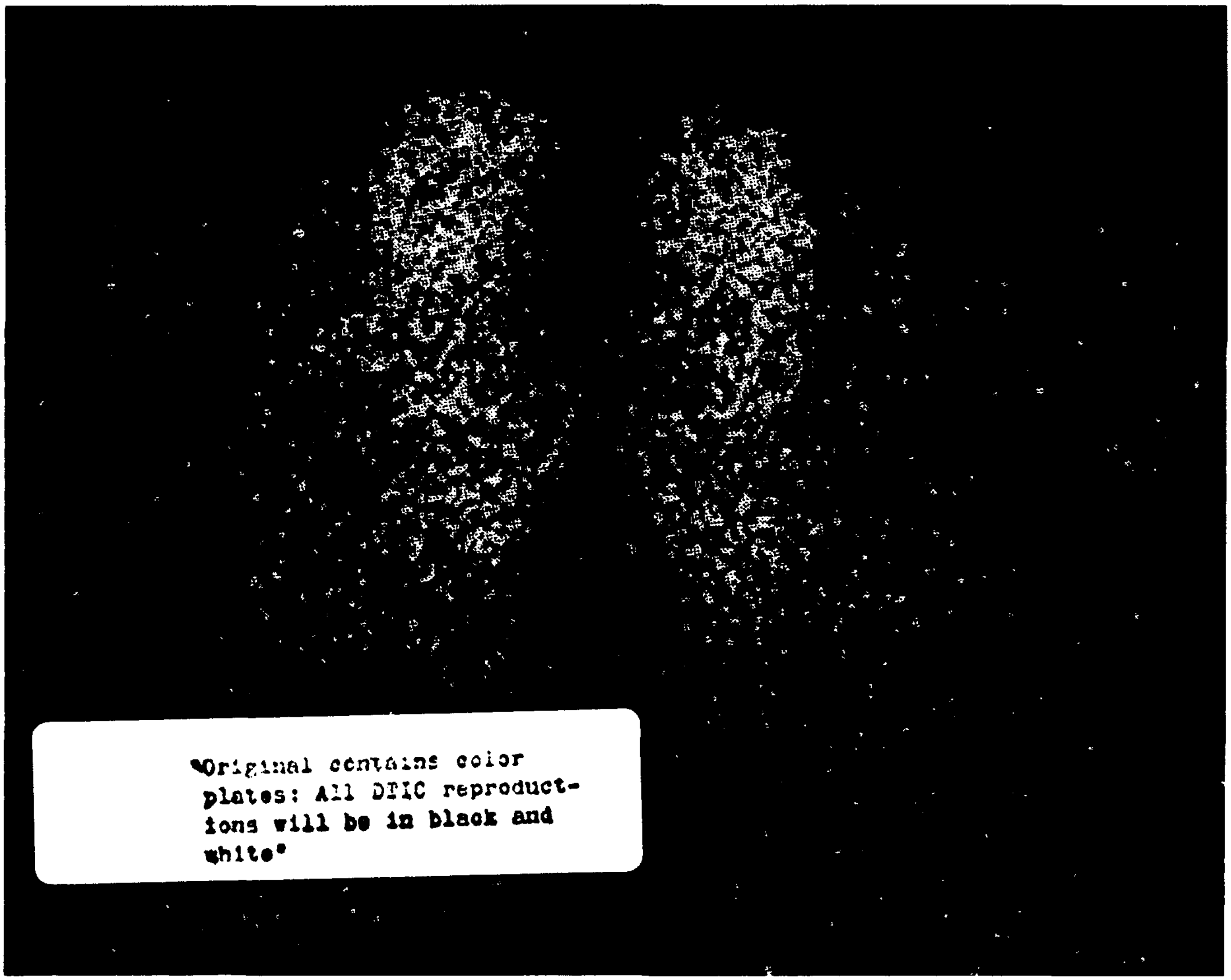
Air Force Office of Scientific Research

1991

RESEARCH HIGHLIGHTS



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Cover Photograph: False color image of a section of the hamster brain at the level of the suprachiasmatic nuclei. The section was stained to highlight transcription control genes. These genes are expressed in response to a single pulse of white light in association with a phase advance of the circadian pacemaker. Red and yellow denote areas of high and moderate activity of these genes. Image produced by Robert Asterisk, Krug Life Sciences. See page 55 for more information on this highlight.

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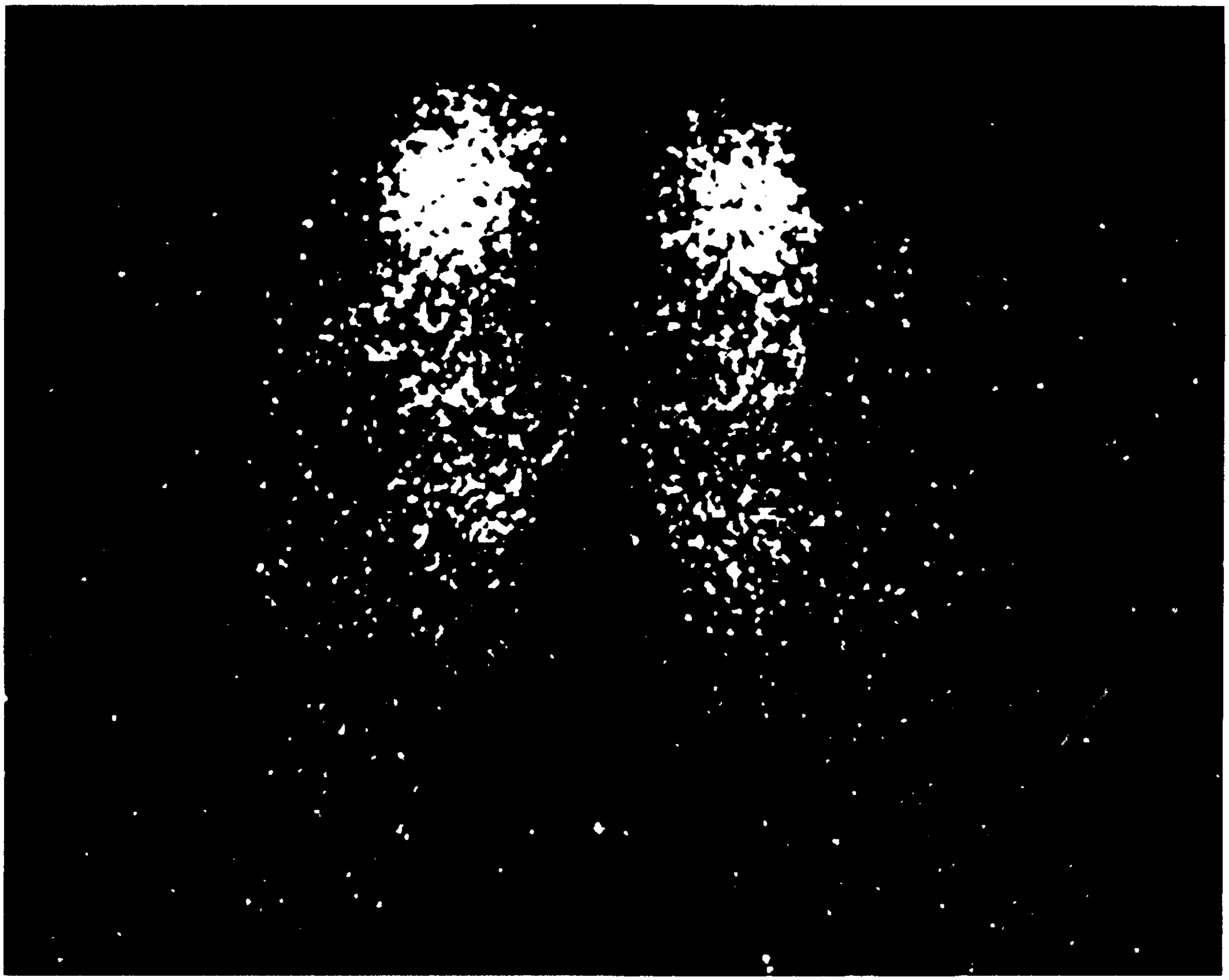
Air Force Office of Scientific Research

1991

RESEARCH HIGHLIGHTS



Bolling Air Force Base Washington, DC 20332-6448

CONTENTS

AIR FORCE BASIC RESEARCH
Challenges in a Changing Environment

This year the Air Force Office of Scientific Research (AFOSR) marks its 40th anniversary. For four decades, AFOSR scientists and engineers have ensured that cutting edge science and technology is available to Air Force and Department of Defense (DoD) laboratories and U.S. industry.

As the events of the last year have clearly shown, we live in an era of rapid change. The reunification of Eastern Europe, allied victory in the Persian Gulf conflict, and the collapse of Soviet communism all tell us the future holds great promise and opportunity.

AFOSR also continues to face new challenges. How can we ensure that the technological superiority we enjoyed in Desert Storm will continue in the future? How do we maintain a strong national defense with budgetary constraints? How do we effectively counter threats stemming from increasingly easy access to the latest technology? How do we as a Nation successfully compete in a rapidly changing technological environment?

Our program managers are directly addressing these concerns. Our goals include maintaining technological superiority in areas relevant to Air Force needs: preventing technological surprise from our adversaries; maintaining a strong research infrastructure among Air Force laboratories, industry, and universities; and complementing the Nation's research effort.

We are meeting these challenges with an increased focus on enhancing two-way communication between our "suppliers," those who provide us with new knowledge, and our "customers," those who employ this knowledge to build our technologically superior systems. Our program managers also function as science and technology coordinators. They ensure an effective dialogue between the suppliers, who are organized to research scientific discipline areas such as chemistry and mechanical engineering, and the customers, who create the technology product. Both groups working together ensure the relevance and excellence of our research efforts.

With responsibility for research programs totaling nearly $300 million annually, we manage more than 1,400 grants and contracts awarded to approximately 350 academic institutions, industrial firms, and Air Force laboratories.

World events are causing the Air Force to restructure. As part of that process, the Air Force Systems Command (AFSC) and the Air Force Logistics Command will become the Air Force Materiel Command (AFMC) in July of 1992. The new AFMC will create a truly "cradle-to-grave" approach to systems acquisition.

Last year, AFSC fused its 14 laboratories and research centers into four "super laboratories" to focus on four major technology areas: human factors (Armstrong); space and missiles (Phillips); command, control, and communication (Rome); and air vehicles (Wright).

Organizationally, AFOSR has also adapted. All of our scientific directorates now address both scientific and engineering research efforts. We have also created a comprehensive program to address aerospace environmental sciences and environmental quality. Furthermore, we have renewed our international cooperation through Tri-Service coordination of our offices in London and Tokyo.

A new directorate for Education, Academic, and Industry Affairs was created. Its mission reflects AFOSR's increased emphasis on ensuring future strength through education and placement of highly qualified scientists and engineers, as well as strengthened links with industry. This directorate manages programs for engineering and scientific fellowships, opportunities for university faculty members and graduate students to perform research at Air Force laboratories. Air Force scientists and engineers can also make "hands-on" visits to European laboratories. The directorate also interfaces with U.S. corporations in their research and development programs and manages our small business basic research program.

Clearly, we are charged as never before with responding to the dynamic changes influencing our ability to develop and deploy superior military systems. As we celebrate our 40th anniversary, AFOSR continues to serve our customers by improving the effectiveness and speed of transitioning research accomplishments for Air Force use. In this added role as technology transition agent, we are fostering a partnership between suppliers of knowledge and their technology customers. With this approach, AFOSR is a full partner in the Air Force's quest for ensuring world peace through global reach and global power.

HELMUT HELLWIG
Director

The Basic Research Technology Area Plan contains additional program information. Contact: Defense Technical Information Center at (703) 274-7633.

Table 1. AIR FORCE LABORATORIES RECEIVING FY 92 INTRAMURAL RESEARCH SUPPORT

Wright Laboratory:
- Aeropropulsion and Power Directorate
- Armament Directorate
- Avionics Directorate
- Flight Dynamics Directorate
- Manufacturing Technology Directorate
- Materials Directorate
- Solid State Electronics Directorate

Rome Laboratory:
- Electromagnetics and Reliability Directorate
- Intelligence and Reconnaissance Directorate
- Surveillance and Photonics Directorate

Phillips Laboratory:
- Geophysics Directorate
- Laser Imaging Directorate
- Propulsion Directorate
- Space Technology Directorate

Armstrong Laboratory:
- Aerospace Medicine Directorate
- Crew Systems Directorate
- Human Resources Directorate
- Occupational and Environmental Health Directorate

Frank J. Seiler Research Laboratory (A detachment of AFOSR)

Air Force Civil Engineering Support Agency

Table 2. CRITICAL TECHNOLOGIES SUPPORTED

	AFOSR SCIENTIFIC DIRECTORATES				
DOD Critical Technologies (1 May 1991)	Aerospace Sciences	Chemistry & Materials Science	Physics & Electronics	Life & Environmental Sciences	Mathematical & Computer Sciences
Semiconductor Materials & Microelectronic Circuits		B	A		
Software Engineering				A	A
High Performance Computing				A	A
Machine Intelligence and Robotics	B			A	A
Simulation and Modeling	A		B	A	A
Photonics		A	A		
Sensitive Radar			A		B
Passive Sensors	B		A		B
Signal & Image Processing			B		A
Signature Control	B	A	B		
Weapon System Environment	A	A	B	A	B
Data Fusion				A	B
Computational Fluid Dynamics	A				A
Air Breathing Propulsion	A	A	B		B
Pulsed Power			B		
Hypervelocity Projectiles & Propulsion	A				
High Energy Density Materials	B	A	B		
Composite Materials	A	A			B
Superconductivity		B	A		
Biotechnology		A	B	A	
Flexible Manufacturing	B				B

KEY
A = FY 92 Major Support (> $ 1 Million)
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DIRECTORATE OF AEROSPACE SCIENCES

The Directorate of Aerospace Sciences is responsible for stimulating and managing basic research in the disciplines of solid mechanics and structures, fluid mechanics, and propulsion.

Research in solid mechanics and structures is organized into the areas of structural mechanics, structural dynamics, mechanics of materials, and civil engineering. The program in structural mechanics addresses the need to better understand the fundamental solid mechanics issues that govern the mechanical behavior of materials and structures, including damage growth and inelastic behavior. This program is currently focused on determining correlations between imperfections and damage and the resulting material and structural responses. The structural dynamics program is focused on the dynamics, aeroelasticity, and control of aerospace structures. In recent years, considerable emphasis has been placed on the nonlinearities arising from interactions such as those between control devices and structures. Research in the mechanics of materials seeks to establish the fundamental understanding required to predict the mechanical performance of aerospace structural materials. Recent efforts have concentrated on developing the mechanics methodology for dealing with several emerging classes of multiphase materials. Current emphasis is on material systems capable of operating in severe, high-temperature environments, including ceramic materials, metal-matrix composites, and carbon/carbon composites. Research in civil engineering, which seeks the understanding necessary to predict the effects of weaponry on civil engineering materials and structures, is organized into two programs: soil mechanics and structural and material response. The focus of both programs is on characterizing the deformation and failure of civil engineering materials and structures subjected to rapid loadings, such as shock and impact.

Research in fluid mechanics provides fundamental scientific knowledge about the behavior of complex flows associated with aerospace vehicles and flight regimes important to the Air Force. The program emphasizes the development of computational methods for accurate and efficient numerical solution of the equations of fluid dynamics; the role of turbulence in the prediction and control of shear flows; the dynamics of unsteady, separating flows such as those occurring during rapid vehicle maneuvers; and the complex internal flows found in gas turbine engines. In other research in this program, supercomputers are playing an increasingly important role in helping us understand the fundamental physics of turbulent flows. An article featured on the cover of the January 1990 issue of *Physics Today* outlines progress and challenges in this area.

Research in propulsion involves the efficient use of energy in Air Force propulsion and weapon systems. The program is organized into the areas of space power and propulsion, air-breathing combustion, and diagnostics in reacting media. Rocket and space propulsion addresses solid-fueled rocket combustion instabilities, electromagnetic thrusters, and chemical formulation of high-energy propellants. Air-breathing combustion includes research on supersonic combustion, turbulent reacting flows, and inhibition of soot formation. Research on supersonic shear layer combustion has revealed the presence of three-dimensionality believed to be responsible for the suppression of fuel-air mixing and local shock structure. Research efforts dealing with diagnostics in reacting media have been devoted to multidimensional, multiparameter, gas-phase measurements and measurements of droplets and sprays. Significant progress has been made on the use of planar, laser-induced, fluorescence measurements in hypersonic propulsion testing environments.

Modern Stability Research Improves Understanding of Nonlinear Structural Dynamic Behavior

Achievement

Researchers at Cornell University have contributed to a better understanding of the complicated behavior of nonlinear structures, based on the modern stability concept. For the first time, both experiments and theory have been combined to investigate the coupled bending-torsional vibrations of an elastic rod from a global, intrinsically nonlinear point of view. A previously undiscovered family of asymmetric bending-torsion modes has been found, and the complete dynamic feature of the system has been characterized.

Background

For years, knowledge of dynamic behavior of elastic rod has been limited to the state of small, planar vibrations. To design future high-performance structural and material systems, it is critical that nonlinear behavior of flexible structures is understood and accurately predicted.

A flexible structural system can become chaotic because it is sensitive to the initial conditions (figure 1). Recent interests of chaotic phenomena in mechanics have advanced the development of nonlinear theory in stability. The modern stability concept can be used to predict highly nonlinear behavior of structures under forced vibrations. The researchers of this work unit intend to determine the "random" appeared motions between the equilibrium states of an oscillating beam subject to forced excitations.

The experimental program engages in measuring the dynamic response of an elastica, a three-dimensional elastic rod.

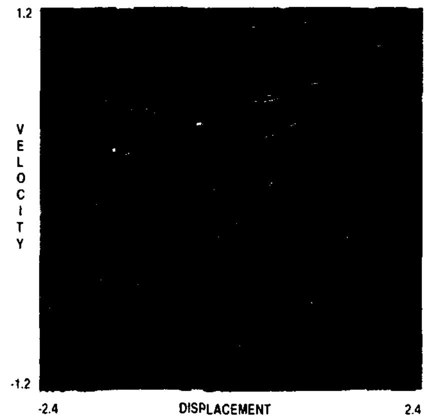


Figure 1. *This photo describes the basins of attraction for two different motions of a buckled structure. The two axes represent the initial position and velocity of the system. The fractal mixing of the colors indicates a sensitive dependence of the dynamics on initial conditions and represents a precursor of chaotic vibrations.*

The elastica is clamped at the support end and oriented so that its undeformed neutral axis is vertical. The support of the rod is harmonically displaced by electromechanical shaker. Stable motions are observed in which the response of the rod is planar. Measurements with optical and computerized devices show that the unplanar motions, torsional responses, initiate when the system becomes unstable (figures 2 and 3). Regions of instability are determined in terms of system frequency, as shown in figure 4. Resonances occur not only at all the in-plan natural frequencies but also at the combination resonances at the frequencies of the planar and nonplanar modes.

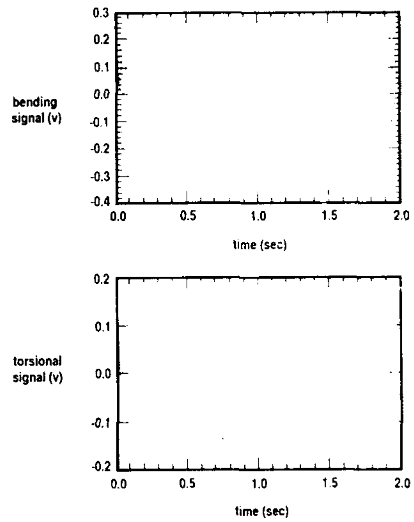


Figure 2. *Responses before and after instability.*

Figure 3. *Nonplanar motion.*

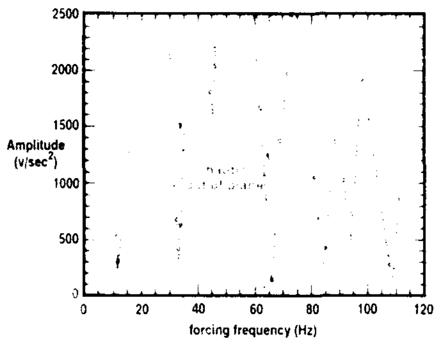


Figure 4. *Stability boundary for the elastica.*

Payoff

The findings improve the fundamental knowledge of the dynamic behavior of nonlinear systems and enhance the ability of active control of large flexible structures, including precision space systems.

Contributing Organizations and People

Professors F. Moon, P. Gergly, J. Thorp, and J. Abel at Cornell University performed this research as part of a program managed by Dr. Spencer Wu of the Directorate of Aerospace Sciences.

Temporal Evolution of Three-Dimensional Turbulent Mixing in Gases Measured Successfully

Achievement

A new measurement technique based on detecting laser light scattered by aerosol particles has provided the first quantitative information about the temporal variations that occur in three-dimensional gas-phase mixing processes. Such measurements have not been possible previously because it is necessary to make measurements throughout a spatial volume in less than a thousandth of a second, representing a requirement apparently beyond practical capability.

Background

Turbulent flow and transport processes occur widely in both technology and nature. For many technological applications, failure to understand and control turbulent transport results in severely degraded performance. In Air Force propulsion technology, turbulence controls the mixing of fuel and oxidizer to form a combustible mixture. For decades, traditional design methods for propulsion systems relied on trial-and-error testing of prototype configurations. Such tests have become prohibitively time consuming and expensive and seldom lead to the performance expected from theoretical thermodynamic considerations.

In recent years, computational combustion models have become an important adjunct to traditional propulsion system design approaches, resulting in considerable savings in development time and cost for emerging gas turbine engines. In the future, propulsion systems for hypersonic aircraft and transatmospheric vehicles will be even more dependent on computer-based design because hardware testing capability will be extremely limited. Unfortunately, deficiencies in understanding turbulent mixing and combustion have limited the utility of computer codes to *qualitative,* as opposed to *quantitative,* design functions. Basic research experiments that provide detailed measurements of turbulent behavior are needed to validate and improve computational combustion models to achieve quantitative prediction capability.

The ability to make temporally and spatially resolved, three-dimensional measurements of turbulent behavior is critical because turbulent mixing is highly nonuniform and transient. Accurate computer models of this process can be developed and tested only by examining detailed experimental data. The measurements illustrated in figure 1 provide the initial demonstration of a capability to provide the requisite data.

These measurements were made by decomposing a laser beam into four component wavelengths of 355 nm, 396 nm, 532 nm, and 690 nm. Optical means were then employed to form the laser beams into four closely spaced sheets of light. Figure 1 shows the scattering of this laser light produced by aerosol particles seeded

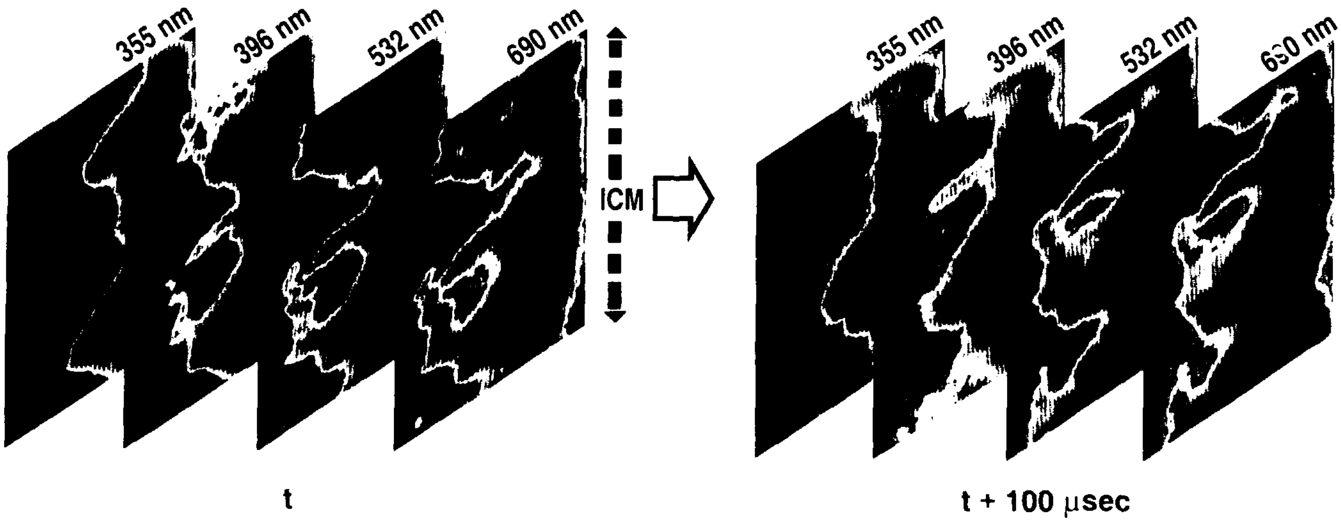


Figure 1. *Snapshots of chemical concentration contours.*

into a flame of hydrogen and methane mixed with air. The images are recorded on a single solid-state detector, with the different planes of light separated by optical filtering. Variations in the images occur as the particles are consumed by the flame. Each sheet of laser light provides a two-dimensional measurement, and a comparison of scattering between adjacent light sheets adds information about variations in the third spatial dimension. From these images it is possible to determine the turbulent flame speed. It is noteworthy that the two sets of images in the figure are separated in time by 100 millionths of a second, reflecting the ability to resolve all transient behavior that occurs.

Payoff

Information about turbulent flame speed, as well as other turbulence parameters, produced by this new measurement capability will provide the data base needed to improve computational combustor design models. These models will be used to produce aircraft and weapon propulsion systems with improved efficiency, lower fuel consumption, and reduce signature compared with current systems. Future research will provide additional information about the concentration of chemical species associated with the combustion process and the three-dimensional velocity field.

Contributing Organizations and People

Dr. Marshall Long performed this research at Yale University as part of a program managed by Dr. Julian Tishkoff of the Directorate of Aerospace Sciences.

3-D Analysis Seeks to Quantify Influence of Debonding Mechanisms on the Crack-Growth Resistance of Ceramic Composites

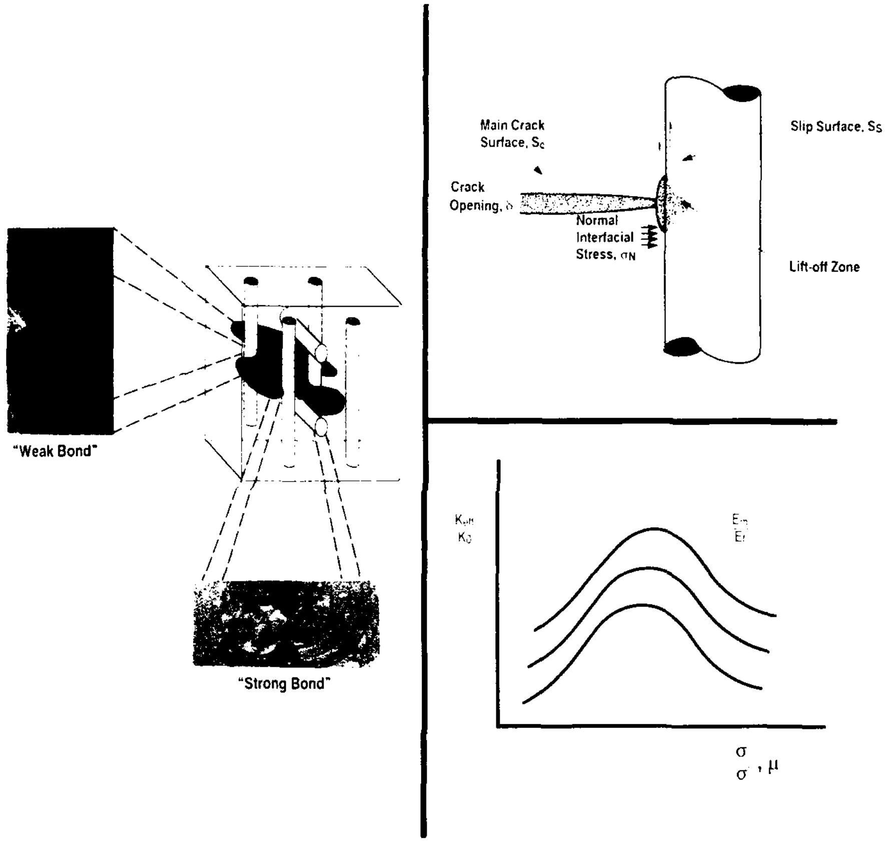
Achievement

The significance of the theoretical work is that it is the first true 3-D study of its kind. While a number of researchers have looked at a crack near a frictional interface as a 2-D or axisymmetric geometry, the complex nonlinear problem of a crack interacting with a frictional interface is inherently a 3-D phenomenon. The computational labor involved in applying a 2-D approach to this problem has dissuaded, until now, any serious 3-D modeling of the mechanics of a moving fracture that encounters a fiber or an inclusion with friction at the interface.

Background

The challenge is to design ceramic composites that retain excellent strength and temperature qualities yet fail in a less catastrophic manner. The design of such composites requires analyses that accurately model the important features of cracks growing in multiconstituent media.

The objective of this analysis is to determine the optimal combination of physical properties to meet the maximum toughening effect in the brittle matrix/brittle fiber composites.



Figures 1a, 1b, and 1c. *Cracks at the interfaces of a fiber-reinforced composite material system are investigated in order to quantify the influence of debonding mechanisms on crack-growth resistance.*

Experiments conducted with varying degrees of frictional bonding between the matrix and the fiber show that the interfacial bonding has a pronounced influence over the character of crack growth in the vicinity of a fiber (figure 1a). The strength of the interfacial bonding is controlled through coatings applied to the fibers before casting the specimens. The growth of cracks near a fiber presents a clear picture of how the material properties and the fiber geometry affects the shape of the fracture as it grows toward and around the fibers. If the fiber is perfectly bonded to the matrix the resulting composite is a relatively brittle material. Alternatively, if the fiber is weakly bonded to the matrix, the resulting composite is a relatively tough material.

Since the mechanisms that hold the key to improved toughness are the frictional interaction and lift-off at the interface ahead of a crack, a 3-D computational methodology has been developed that allows for the asymmetric development of an interfacial shear crack on a cylindrical surface (figure 1b).

The current focus of this research is to specifically evaluate the interaction of

the main crack with interfacial slipping and lift-off.

Once the micromodel of a crack bending and bowing around a single fiber with a frictional interface is verified, it will be possible to quantitatively assess how cracks grow in the presence of an array of fibers with a general set of imposed loads, including the thermal stresses induced by the anticipated harsh operational environments these materials will endure. With these results, a set of design rules can be constructed to assist the material scientist in developing useful composites that meet today's challenging design requirements (figure 1c).

Payoff

The demand for materials that can meet today's challenging design requirements in hypersonic aircraft and engine components has stimulated interest in using ceramics in structural applications. Ceramic materials are noted for their ability to withstand loads at very high temperatures and in aggressive environments. No other class of materials exhibits such excellent physical and chemical properties. While these materials possess many outstanding characteristics, they are inherently brittle and, hence, are susceptible to catastrophic failure. Numerous studies have shown that ceramics can be made more crack resistant by incorporating fibers and by appropriately controlling the interface of the matrix and the fibers.

Contributing Organizations and People

This research is being conducted under the direction of Professor Michael Cleary at MIT, assisted by Dr. William Keat and Capt. Michael Larson. The program was initiated by Lt. Col. George Haritos and is under the management of Lt. Col. Steve Boyce of the Directorate of Aerospace Sciences.

Control of Compressor Surge Achieved

Achievement

Basic experimental and theoretical research at the MIT Gas Turbine Laboratory has led to the development of a lumped parameter model of engine compressor systems. This model provides a useful system model for controlling both surge and rotating stall. Rotating stall is a higher order compressor instability in which adjacent blades participate sequentially in local flow separation (blade stall), which propagates circumferentially around the rotor of a given compressor stage. Rotating stall can trigger compressor surge; controlling rotating stall can also prevent compressor surge. The two instability modes are illustrated schematically in figure 2.

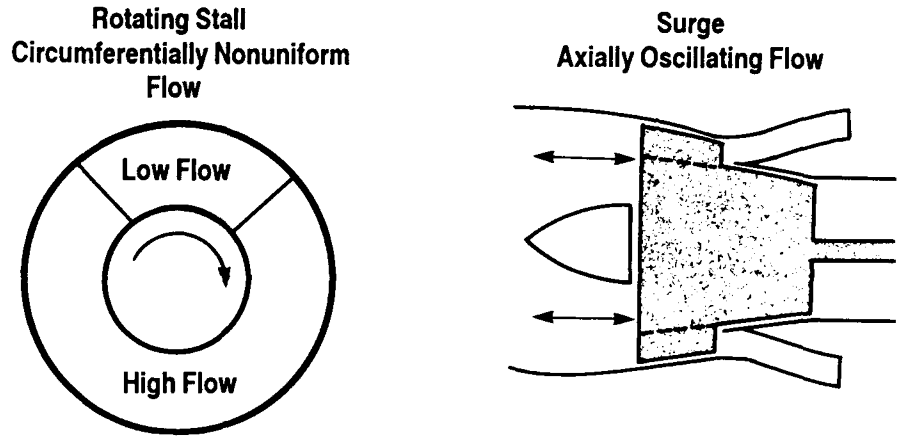


Figure 2. *Compressor flow instabilities.*

Research on active surge control strategies has also led to successful suppression of surge in centrifugal compressors. For example, feedback control of a variable throttle valve placed at the compressor exit has been successfully demonstrated. The MIT research has also explored active control of rotating stall in axial flow compressors. One concept uses movable inlet guide vanes to launch circumferential waves of pressure in response to detected precursor waves associated with the natural rotating stall instability. The baseline theory of compressor instabilities developed under the AFOSR program has led to collaborative AFOSR/ONR support of further research on rotating stall control in axial compressors, and is now being examined by researchers at the Air Force Wright Laboratory for possible transition to exploratory development programs associated with the Integrated High-Performance Turbine Engine Technology Program.

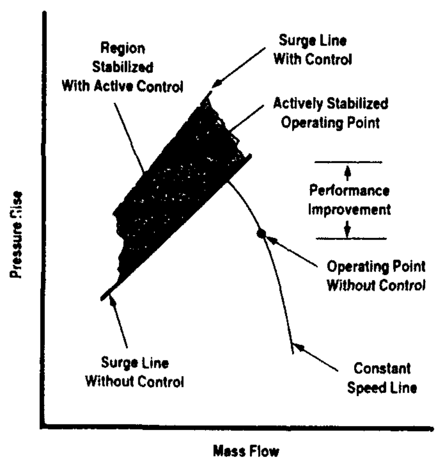


Figure 1. *Goals of dynamic compressor stabilization.*

Background

Compressor surge is a fundamental turbomachinery instability that severely constrains the design and operation of jet engines. In its simplest form, surge is characterized by very large oscillations in the mass rate of flow of air through the entire engine, sometimes producing reversed flow and potentially catastrophic engine failure. Surge is avoided in practice, though not always successfully, by conservatively operating the engine compressor 25 percent below the maximum possible pressure ratio. A typical compressor pressure rise characteristic is shown in figure 1. This figure also illustrates that control of compressor surge will allow jet engines to operate at much higher pressure ratios without sacrificing safety. This translates to higher thrust and lighter weight engines with lower fuel consumption.

Surge can occur in centrifugal flow compressors such as those often used in turbochargers, and in axial flow compressors such as those used in jet aircraft engines. Since the theoretical model developed at MIT is sufficiently general to include either system, surge control was first studied in centrifugal compressors where rotating stall does not occur. A simple concept for surge control, shown schematically in figure 3, uses a simple tailoring of the structural properties of a flexible plenum chamber wall so that the wall motion can interact with the fluctuating pressures produced by the flow in such a way that internal damping in the wall stabilizes the compressor operation. Figure 4 shows that a 25 percent reduction in the mass flow at the onset of surge has been achieved. While the pressure rise in the low-speed research compressor is essentially the same with and

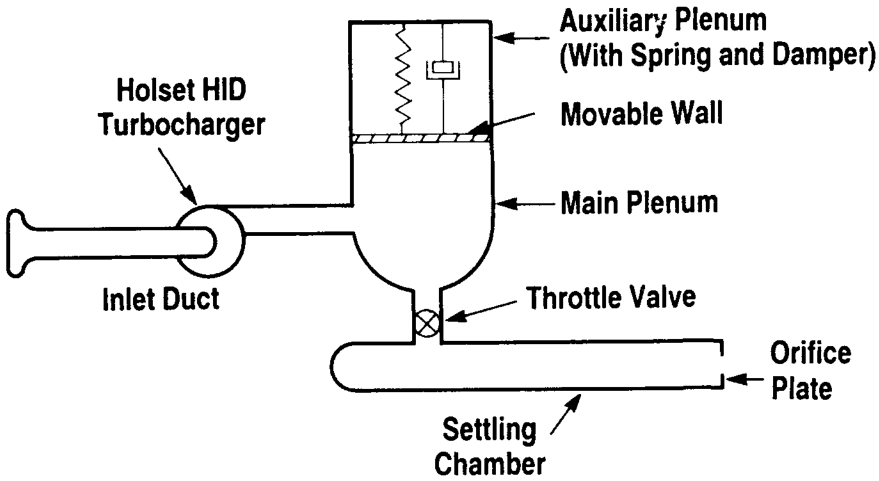


Figure 3. *Schematic of experimental facility.*

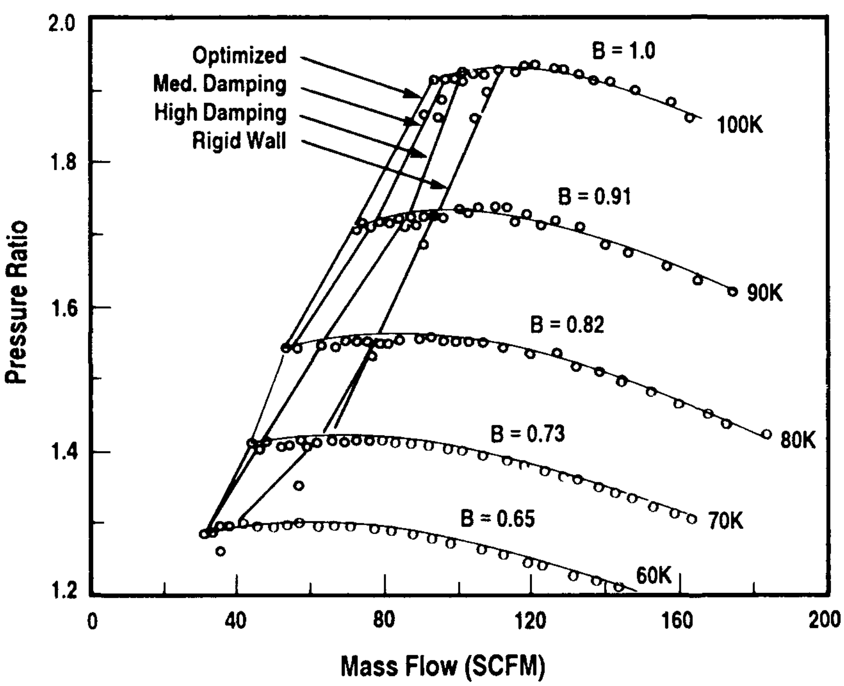


Figure 4. *Compressor performance map.*
— Fixed and Movable Wall —

without control, reducing the mass flow in a high-speed engine compressor will raise the pressure ratio as already illustrated in figure 1.

Payoff

More sophisticated concepts for structural tailoring include deformable shrouds that can modulate blade tip clearance flows in a favorable way to enhance aerodynamic and structural damping. Such approaches to rotating stall control have high potential payoffs for gas turbine engines of the future.

Contributing Organizations and People

This research has been conducted by an interdisciplinary team led by Professors Greitzer and Epstein of the Gas Turbine Laboratory at the Massachusetts Institute of Technology under the joint sponsorship of the Directorate of Aerospace Sciences and the Directorate of Mathematical and Computer Sciences. The research has been supported by programs managed at AFOSR by Dr. James McMichael, Maj. Dan Fant, and Dr. Marc Jacobs.

Quasi-Steady Plasma Sustained With Pulsed Free Electron Laser

Achievement

Previous research has established that steady plasmas can be sustained in flowing gases using continuous-output infrared lasers, but the development of high-power lasers is currently directed toward pulsed systems. Quasi-steady high temperature plasmas have been ignited and sustained in flowing argon at pressures from 1 to 3 atmospheres using the repetitively pulsed beam produced by the Los Alamos free electron laser (FEL).

Background

Figure 1 is a series of high-speed photographs showing ignition of the plasma, growth to a quasi-steady plasma, and subsequent decay when the beam is switched off. The laser operated at a wavelength of 10.6 microns and produced an 80-microsecond-long burst of 1,740 pulses. The average power during the burst was 10 kW. Each pulse had a duration of only 10 picoseconds and the pulses were separated by 46 nanoseconds. Spectroscopic measurements of the plasmas gave plasma temperatures of approximately 20,000 K and showed no variations in plasma conditions during the 46-nanosecond intervals between the individual laser pulses.

Argon plasmas were easily ignited and sustained over a range of laser power, but it was not possible to ignite and sustain plasmas in either nitrogen or hydrogen using the Los Alamos laser. A theoretical investigation of picosecond plasma breakdown was undertaken, since the existing predictions of breakdown thresholds for 10-picosecond pulses were similar for these gases. A detailed model incorporating electron-atom elastic, inelastic, vibrational, dissociating, and ionizing collisions indicated that breakdown did not occur at the first pulse. Instead, a cascade of increasing ionization in the focal volume was produced by the absorption of subsequent pulses and led to breakdown after approximately 10 pulses.

Gasdynamic expansion due to heating of the gas in the focal volume is minimal for the 10-picosecond duration of a single pulse, but may become important over the 46-nanosecond interval between pulses. Gasdynamic expansion leads to reduced density in the focal volume and the subsequent pulse is not as strongly absorbed. An approximate model based on the classical Taylor-Sedov similarity solution for a point expansion indicates that the expansion in hydrogen and nitrogen occurs faster than for argon. The reduction in electron density caused by this expansion may limit absorption of subsequent laser pulses below that required to reach ignition threshold, as illustrated in figure 2. A more detailed numerical model for multiple pulse breakdown that incorporates gasdynamic expansion into the detailed collisional model is currently under development.

Payoff

Plasmas can provide high-temperature propellants that greatly improve the specific impulse of space thrusters. These plasmas could be sustained either by electrical discharges using onboard spacecraft power or by energy beamed to the spacecraft using microwaves or lasers.

Contributing Organizations and People

This research was performed by Dr. Dennis Keefer at the University of Tennessee Space Institute as part of a program managed by Dr. Mitat Birkan in the Directorate of Aerospace Sciences.

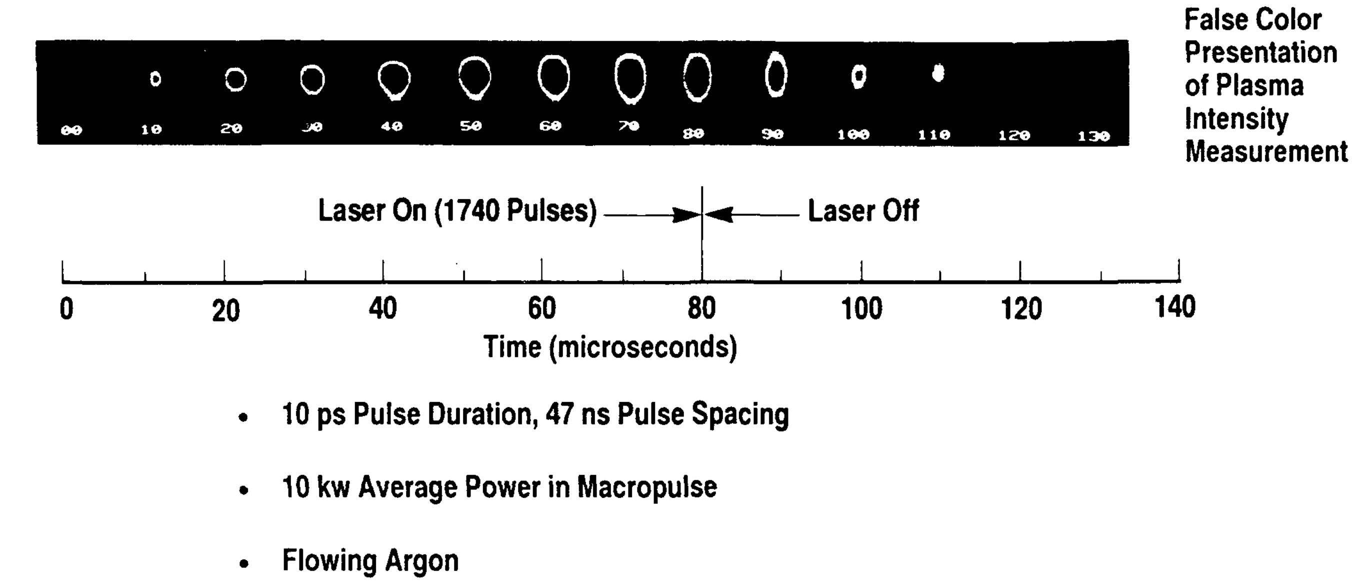


Figure 1. *Preliminary experiments indicate that quasi-steady plasma may be sustained by repetitive pulsed laser.*

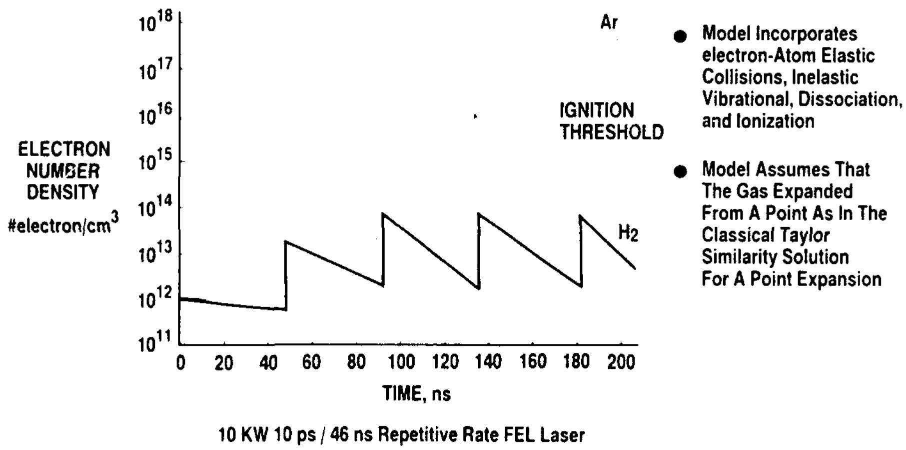


Figure 2. *Hydrodynamic expansion model predicts that argon plasma will be sustained but hydrogen plasma will not be sustained by existing repetitive pulsed laser.*

Turbine Cooling Enhanced by Total Temperature Separation

Achievement

Basic experimental research conducted at the University of Washington has focused on enhancing impingement cooling by taking advantage of the total temperature separation induced by the formation of primary and secondary vortical structures. Laboratory tests have indicated that this mechanism may increase cooling effectiveness as much as 430 °F in the turbine thermal environment.

Background

Impingement cooling is of great importance, as it is used to cool the leading edges of turbine blades, which are exposed to the highest temperatures and heat transfer rates. In this scheme, high-pressure air, bled from the compressor, is brought through a tube to the inside of a hollow turbine blade. Jets of air are then directed toward the inside surface of the leading edge and midchord regions through small holes drilled in the tube, as shown in figure 1. Similarly, impinging jets of air are often used to cool high-temperature combustor liners.

This phenomenon was modeled by using a free jet impinging on a circular flat plate. The secondary vortices, shown schematically in figure 2, are induced by the primary vortex rings (formed at the nozzle lip) through the following mechanism: the approach of the primary vortex, with its low-pressure center, generates an unsteady adverse pressure gradient on the impingement plate, which causes the boundary layer on the plate surface to separate and roll into a counter-rotating secondary vortex ring. Both the primary and secondary vortex rings separate the total temperature into hot (H) and cold (C) spots. Notice, in particular, the cold spots on the impingement plate surface, which are induced by the secondary vortex ring. A closer view of this vortical structure is depicted in figure 3. Here, the secondary vortices (in red) form a "cold blanket" shielding the impingement plate from the primary vortices (in blue). This "cold blanket" persists near the surface of the plate and translates into

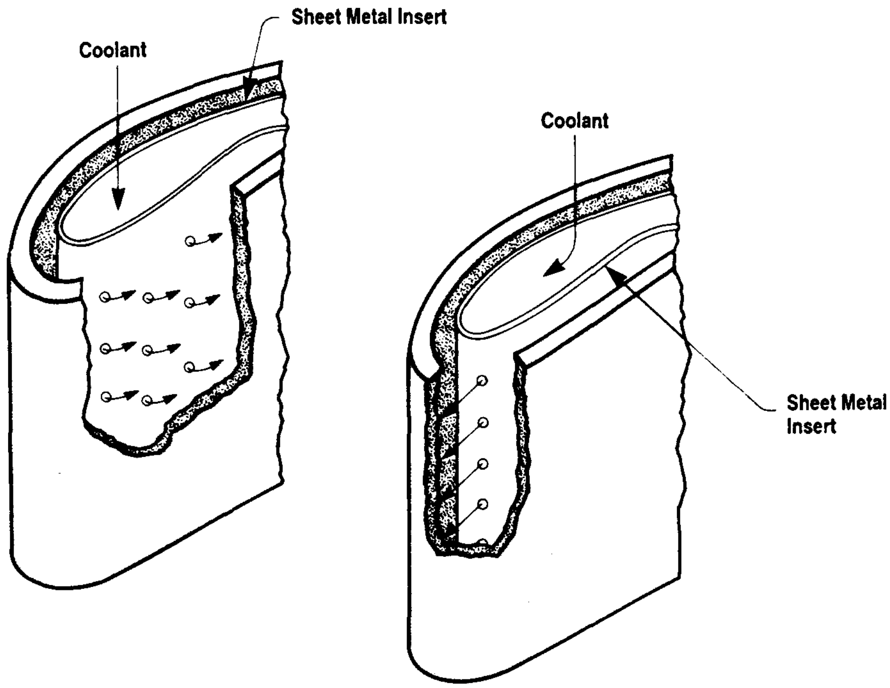


Figure 1. *Impingement cooling in turbine blades.*

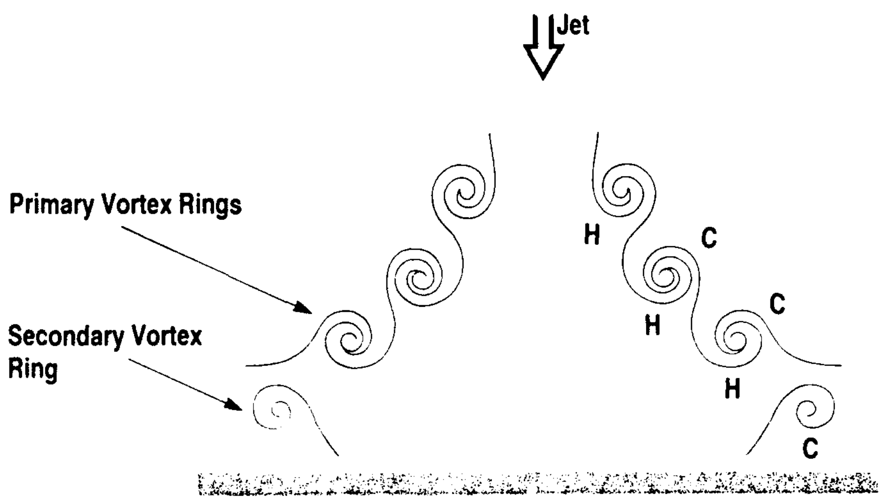


Figure 2. *Total temperature separation in an impinging jet.*

Figure 3. *Primary and secondary vortices in an impinging jet.*

enhanced cooling effectiveness in an actual turbine environment.

Future research will extend this work to include the effects of wall curvature and rotation on the total temperature separation process. Also, the influence of acoustic excitation on heat transfer will be pursued. This latter phenomenon shows promise of strengthening the secondary vortices near the impingement plate, which in turn should increase the magnitude of the cooling on the surface.

The current research has fostered an improved understanding of the physics behind vortex-induced total temperature separation. The researchers' experimental model has successfully demonstrated the cooling enhancement that may be achieved when secondary vortices are allowed to form and shield the surface of the impingement plate. These results offer great encouragement for further enhancement of turbine cooling.

Payoff

The thrust-to-weight ratio of 21st-century military aircraft engines is envisioned to be more than twice that achieved with today's technology. To achieve this target, turbine inlet temperatures will have to be raised from the current level of 2400 °F to over 3600 °F. Although advances in material technology are necessary to reach this goal, it is imperative that a substantial gain in turbine blade cooling be achieved concurrently without weight penalty.

Contributing Organizations and People

This research was performed by Professor Kurosaka, and graduate students Michael Fox and John O'Callahan, at the University of Washington, and was supported by AFOSR under a program managed by Maj. Dan Fant and Capt. Hank Helin of the Directorate of Aerospace Sciences.

Vortex Interactions Influence Heat Transfer Near the Base of Turbine Blades

Achievement

This research conducted at Lehigh University uses experimental and numerical techniques to study the dynamics of three-dimensional vortex evolution and interaction. These studies have revealed a surface-layer eruption process that may be the key mechanism influencing surface heat transfer near the base of the turbine blade.

Background

The experimental work was done in a water channel using a turbine blade mounted with its axis normal to a flat plate. The impingement of a laminar boundary layer, formed over the flat plate, on the blade-wall junction causes the formation of three-dimensional "horseshoe vortices," as shown in figure 1. These vortices engirdle the blade such that the outboard portions (the legs) move periodically inward toward the blade wake, as indicated in figure 2. Figure 3 is an end-view photograph of the interaction of the streamwise extension of the horseshoe vortex legs with the end-wall surface fluid (looking upstream), obtained by using a cross-stream light sheet and two separate hydrogen bubble wires. This figure shows the early phase of the interaction process: the vortex legs impose a local adverse pressure gradient on the viscous flow adjacent to the surface, which causes a rapid focusing of fluid into the sharp, eruptive spire as shown. At a later stage, these eruptions interact with the outer flow and roll over into three-dimensional, mushroom-shaped vortices.

The significance of these results is that vortices close to a surface result in the sharp eruption of surface-layer fluid into the outer region. Figure 4 illustrates this behavior by a sequence of temporal material lines, obtained from a Lagrangian computation of the viscous interaction of a vortex near a surface, which emulates the physical process shown in figure 3. Note that the material line development is relatively slow at the start, but suddenly focuses into a sharp, eruptive spire as a result of the discrete eruption provoked by the action of the vortex-induced local adverse pressure gradient.

Work on horseshoe vortex interactions is continuing, with an emphasis on understanding the impact of three-dimensional vortex structures on temporal surface heat transfer. Since this flow yields a coherent, time-dependent, three-dimensional vortex environment, the opportunity exists to determine the relative effects of vortex-induced behavior, such as surface eruptions, on local time-dependent surface heat transfer.

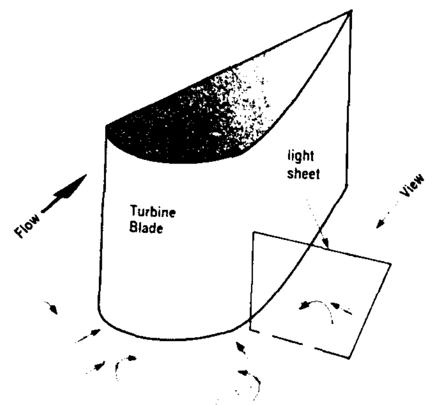


Figure 1. *Vortex formation near base of turbine blade.*

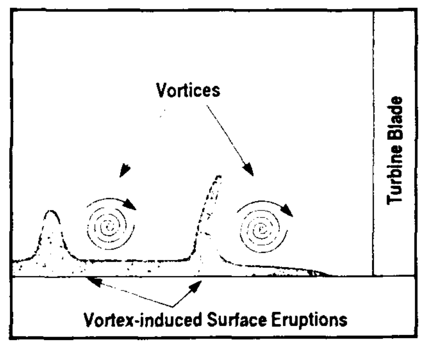


Figure 2. *End view of vortices and induced surface eruptions.*

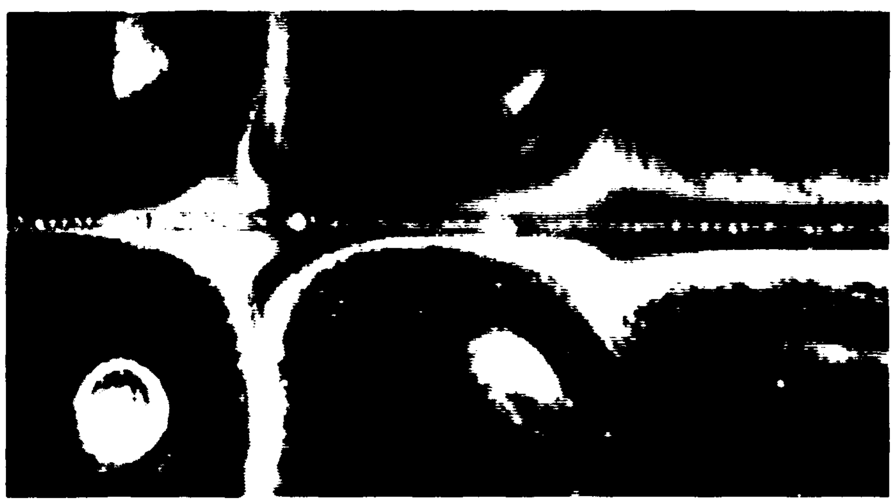


Figure 3. *Visualization of surface eruptions.*

Payoff

Vortical flows generated near the base of turbine blades represent an important example of three-dimensional separation. Understanding the complex fluid mechanics phenomena associated with these flows would enable better surface heat transfer models and provide improved techniques for drag reduction and turbulence control.

Contributing Organizations and People

This research was led by Professors Charles Smith and David Walker at Lehigh University. The program is sponsored by Dr. James McMichael, Maj. Dan Fant, and Capt. Hank Helin of the Directorate of Aerospace Sciences.

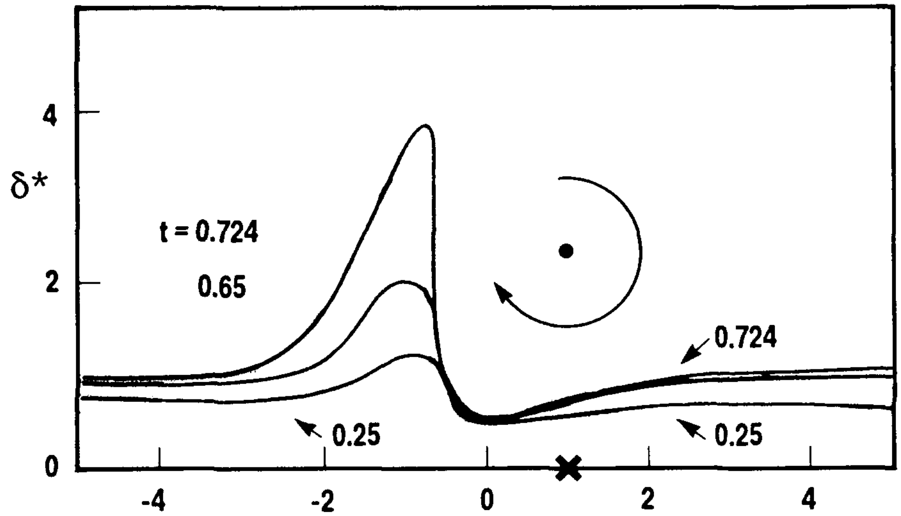


Figure 4. *Computer simulation of surface eruption.*

DIRECTORATE OF CHEMISTRY AND MATERIALS SCIENCE

This year's highlights illustrate a comprehensive research program addressing topics selected for near- and long-term impact on Air Force technology. The directorate's investment in the future emphasizes three major areas: materials (processing, structure, and properties); the interconversion of various types of chemical energy; and the characterization of the overall aerospace environment. This year we highlight the first two topics.

Investigations of materials processing seek new, improved materials or more economic ways to synthesize existing materials. Specific topics include metallurgy, ceramics, inorganic materials chemistry, polymer chemistry, chemical synthesis and reactivity, and theoretical chemistry. Research highlights are presented on the design of ceramic structures, thin-film growth mechanisms for electronic and structural materials, nonlinear optical properties of a select class of molecules, and metal matrix composites.

Energy interconversion refers to the processes by which one form of energy is converted into another. For example, chemical bond energy can be converted into electricity or into the kinetic energy of combustion products. Individual programs include electrochemistry and molecular dynamics. A highlight from research on molecules designed for notably high-energy density is provided. This research seeks the knowledge required for a new generation of rocket propellants.

High-Energy Density Matter: Lithium Atoms in Cryogenic Solid Hydrogen

Achievement

The Propulsion Directorate of the Phillips Laboratory is paving the way toward tomorrow's high-performance rocket propellants. The Phillips team has successfully trapped and stored isolated lithium (Li) atoms in solid hydrogen films frozen at liquid helium temperatures to produce the world's first samples of a metallized cryogenic propellant. Calculations of the performance of such materials used as rocket propellants predict a large improvement over the present state-of-the-art liquid oxygen/liquid hydrogen (LOX/H_2) system.

Background

The technique used to produce the Li/H_2 samples is a variant of the well-known "matrix isolation" method in which reactive "guest" species are trapped in a cryogenic solid matrix of frozen "host" atoms or molecules. The extremely low matrix temperatures and the low chemical reactivity of the matrix hosts stabilize guests that would not otherwise survive. The experiment uses a pulsed laser to create a plume of high-energy lithium atoms. Figure 1 shows a photograph of a laser-ablated lithium plume taken during deposition. The bright plume is a result of emissions from electronically excited Li atoms.

Initial experiments on Li/neon samples showed that the fast Li atoms produced by the laser ablation method were far more efficiently isolated and trapped as atoms than the relatively slow Li atoms produced by traditional thermal methods. In fact, the failure of all previous attempts to isolate Li atoms in neon matrices is documented in both the U.S. and Soviet scientific literature. Success using fast Li atoms led to the development of a microscopic model of the dynamics of the matrix deposition process, which is illustrated in figure 2. In this model room temperature gas condenses to form an "accretion layer" at the surface of the cryogenic solid. This accretion layer is characterized by high mobility of both guest and host species due to the heat released in the solidification processes. This high mobility results in the recombination of Li atoms that are stopped in the accretion layer leading to their trapping as lithium clusters, not as Li atoms. Thus, the improved isolation efficiency is attributed to the penetration of the fast laser-ablated Li atoms through the accretion layer and into previously deposited solid layers of the matrix. There the Li atoms are immobilized. Comparison of spectral line shapes of Li/H_2 samples with atomic Li line shapes is providing the Phillips Laboratory team with information about the structure of the Li atom-trapping sites.

These results are compared to theoretical models calculated using the Cray II supercomputer at Kirtland AFB, New Mexico, by the University of Dayton, Ohio, scientists working with the

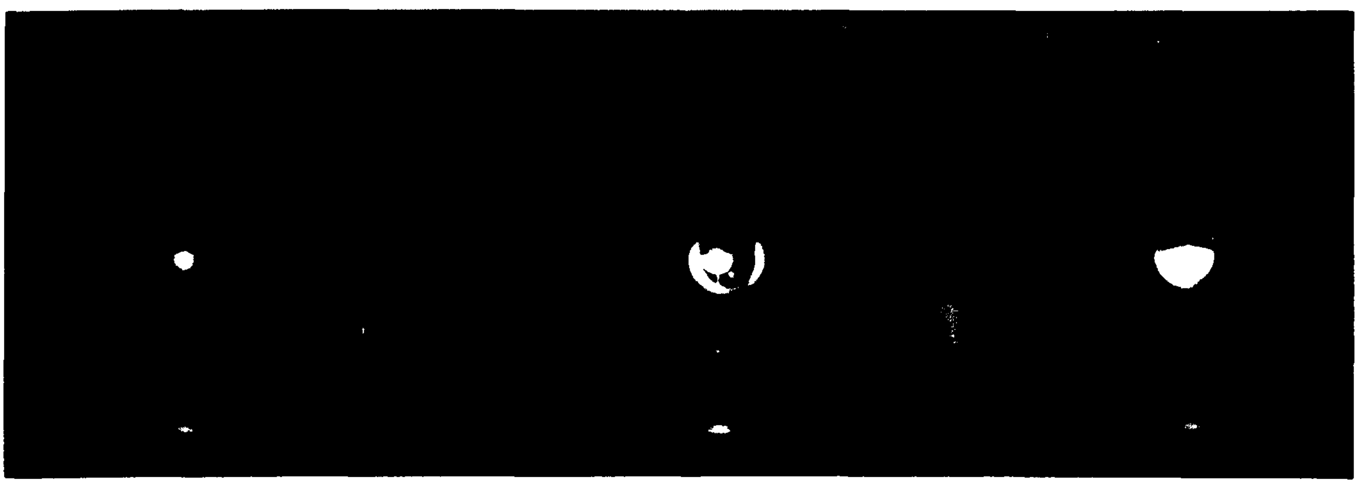


Figure 1. *Photograph of laser ablation plume using a lithium target.*

Propulsion Directorate team. The starting point for the theoretical simulations is calculation of the interaction between a Li atom and a single H_2 molecule; i.e., the Li-H_2 intermolecular potential. The Li-H_2 interaction is an example of a long-range van der Waals interaction that is much weaker than chemical bonding interactions in stable molecules. Paradoxically, this makes the quantum calculation of the Li-H_2 system substantially more difficult than the description of ordinary molecules, as many subtle and normally unimportant effects become significant. Figure 3 shows Li-H_2 potential energy curves as a function of the separation between the Li atom and the center of mass of the H_2 molecule. These calculations are permitting Phillips Laboratory scientists to build models to trap lithium atoms and lithium clusters in solid hydrogen as illustrated by the theoretical model in figure 4. The joint experimental theoretical program has proved to be a very efficient, productive approach to creating new high-energy propellants.

Payoff

The High-Energy Density Matter (HEDM) program, administered jointly by the Phillips Laboratory and AFOSR, has identified metal *atoms* as target additives to future propellant systems. Adding metal *powders* to conventional solid propellant compositions has long been recognized as an effective method of boosting propellant performance; this effect is due to the large amount of energy released when certain metals are burned to form their oxides. If, in addition, the heat of formation of the metal atoms from the bulk metal can also be incorporated into the propellant, energy densities can exceed that of any propellant system in use. Estimates of the performance of Li atom/solid hydrogen fuels burned with liquid oxygen yield an improvement in specific impulse* of approximately 15 percent over the optimized LOX/H_2 propellant. Because the propellant mass is typically a very large fraction of the mass

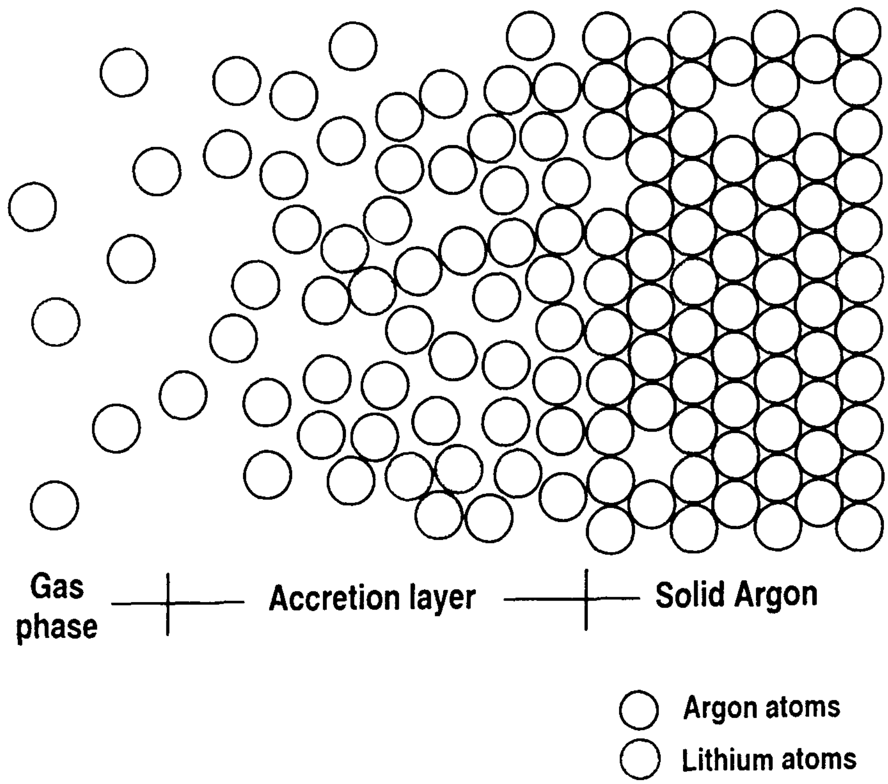


Figure 2. *Deposition model showing transition region or accretion layer between solid argon and gas phase argon. Li atoms deposited into the solid matrix are immobilized while Li atoms deposited in the accretion layer are mobilized and form clusters.*

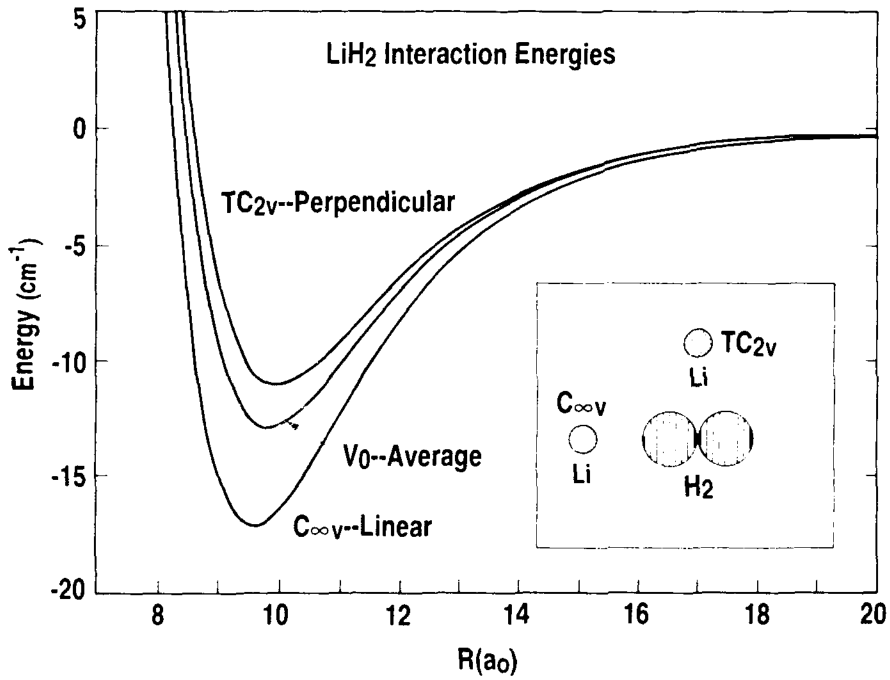


Figure 3. *The curve marked "linear" corresponds to an end-on approach of the Li atom to the H_2 molecule; the curve marked "T" corresponds to an Li atom approach perpendicular to the H_2 bond. Since the H_2 molecule is known to rotate freely in the zero-pressure solid, a spherical average of the linear and T interactions is appropriate to give the mean Li-H_2 interaction. The average is labeled "VO."*

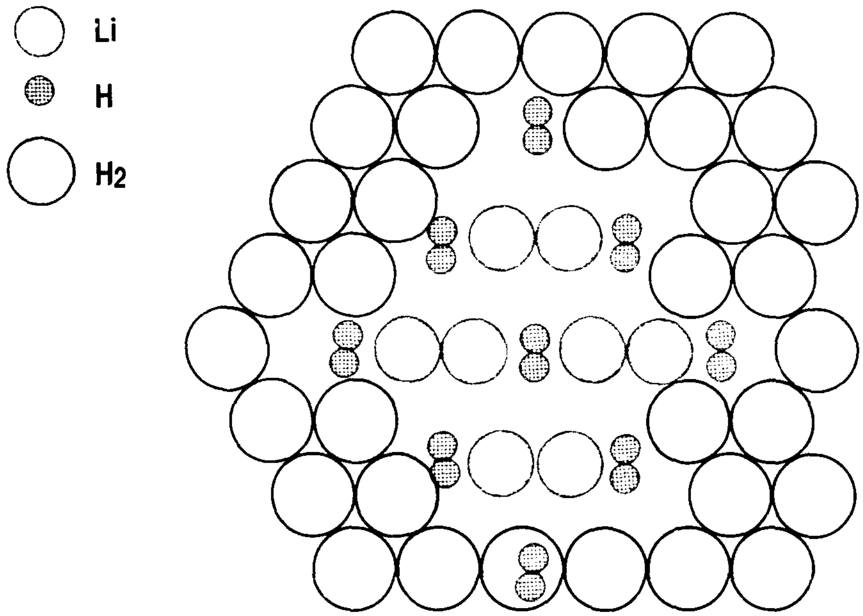


Figure 4. *Hypothetical model for stable arrangement of H_2 and Li_2 in a hydrogen matrix predicted based on theoretical calculations.*

of a fully loaded rocket, this improvement in propellant performance will double the payload capacity of the rocket.

Contributing Organizations and People

This research was performed at the Propulsion Directorate of the Phillips Laboratory at Edwards AFB, CA. The experimental work was performed by Dr. Mario E. Fajardo, and the calculations were performed by Professor David D. Konowalow of the University of Dayton Research Institute; the in-house research effort was managed by Dr. Stephen L. Rodgers.

Specific Impulse: A quantitative measure of performance of a rocket propulsion system. LOX/H_2, the state-of-the-art propellant, has a specific impulse of 500 seconds.

New Growth Directions for Molecular Beam Epitaxy: Opening a Pathway to New Electro-Optical Materials

Achievement

Scientists at the Wright Laboratory Materials Directorate are the first to optimize a molecular beam epitaxy (MBE) technique for layer-by-layer controlled growth of (111) orientation GaAs, AlGaAs, and InGaAs. This advance makes possible applications of an entirely new class of electro-optic (EO) materials for IR sensors, solid-state lasers, and information processing.

Background

Most epitaxial films are grown today by MBE or metal-organic chemical vapor deposition (MOCVD) on (100) orientation substrates. Examining the atomic arrangements of simple unreconstructed (100) and (111) surfaces of GaAs in figure 1 shows them to be very different. The differences in surface structures will naturally lead to quite different surface chemistries and reactivities. It is necessary for good electronic and EO epitaxial materials to have very few imperfections, few impurity levels, and sharp interfaces. These properties are all strongly affected by the growth conditions used to make the films.

Wright Laboratory scientists perform *in situ* film diagnostics during MBE growth using reflection high-energy electron diffraction (RHEED), which gives crystallographic and morphological information. Oscillations in the intensity of the specular RHEED beam have been observed and ascribed to atomic layer-by-layer growth. This type of growth is known to produce films of the highest quality and is the preferable growth condition in MBE. The conditions for optimum growth for (100) films of a wide variety of III–V semiconductors are well established, but at this program's start had not been reported for (111) growth despite a number of attempts by several research groups. There had even been speculation as to whether the surface chemistry of the (111) surface would allow such a growth mode. Recently, scientists at the Wright Laboratory/Materials Directorate have succeeded for the first time in determining the growth conditions for layer-by-layer growth of (111) GaAs. They have extended the work to ternaries such as AlGaAs and InGaAs as well. Effective growth temperatures are much more narrow for (111) GaAs as shown in the RHEED data in figure 2. More precise control of growth conditions overall is required for growth of (111) GaAs compared to (100) GaAs as shown in table 1.

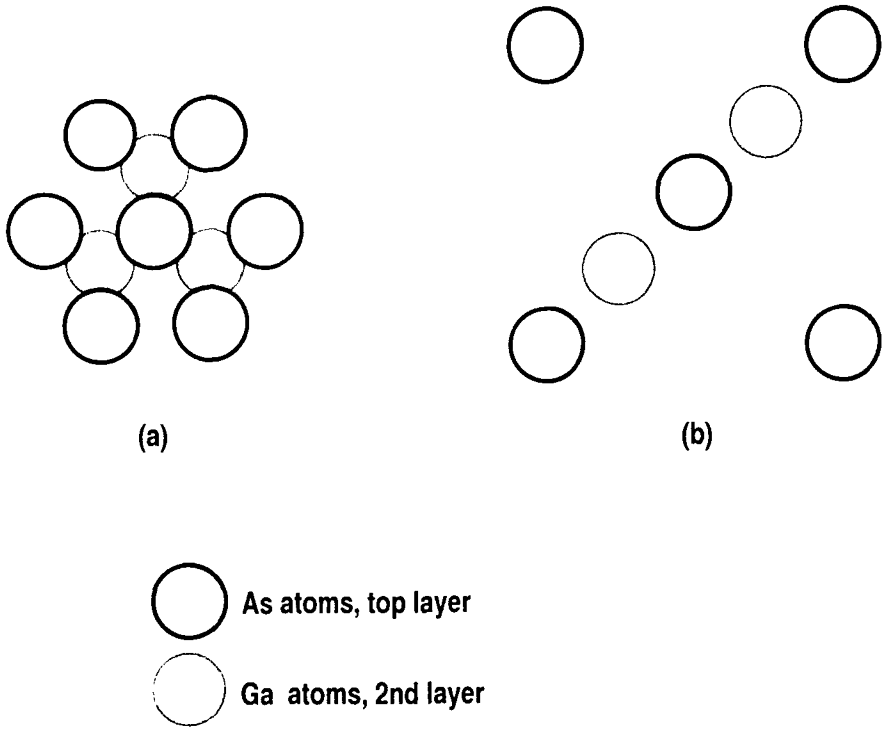


Figure 1. *Atomic arrangements of reconstructed GaAs surfaces. Filled circles represent gallium atoms and open circles represent arsenic atoms. The arsenic atoms occupy the outermost atomic layer and the gallium atoms occupy the second layer. Figure 1a is for the (111) surface and 1b is for the (100) surface.*

Now that conditions for (111) growth have been established, the next step in growing the strained-layer superlattice

(SLS) structures is underway. This will make quality materials available to test theoretical predictions, and open up a whole new class of materials with important Air Force applications.

Payoff

A recent series of publications by D. Smith of Los Alamos Laboratory and C. Mailhiot of Xerox Corp. has predicted a significant advantage to a class of SLS's as EO materials. These SLS's take advantage of the fact that the III–V compound semiconductors such as gallium arsenide (GaAs) are piezoelectric materials, which means that when they are strained, as in an SLS, very high electric fields are set up in the crystal. These fields can produce distortions of the electronic band structure in ways that can lead to favorable EO response. SLS materials are of particular interest to the Air Force due to their predicted potential for high sensitivity, easy processing into long wavelength infrared detector materials, and production of nonlinear optical materials with extraordinarily large nonlinear optical coefficients. A longstanding problem with devices for optical computers is the need for materials with much higher nonlinear optical coefficients. SLS materials have the potential to fill this need. The problem with these materials, however, is that to take maximum advantage of nonlinear optical effects it is necessary to grow the SLS in the (111) growth direction where the piezoelectric effect is maximized. Since most previous epitaxial film growth work was done in the (100) direction, a new growth direction was needed. This capability is now available.

Contributing Organizations and People

This work was carried out at the Wright Laboratory under the technical direction of Dr. T.W. Haas. Dr M.Y. Yen of the University of Dayton was a key participant in the growth studies. The work is part of a program managed by Lt. Col. Larry Burggraf of the Directorate of Chemistry and Materials Science.

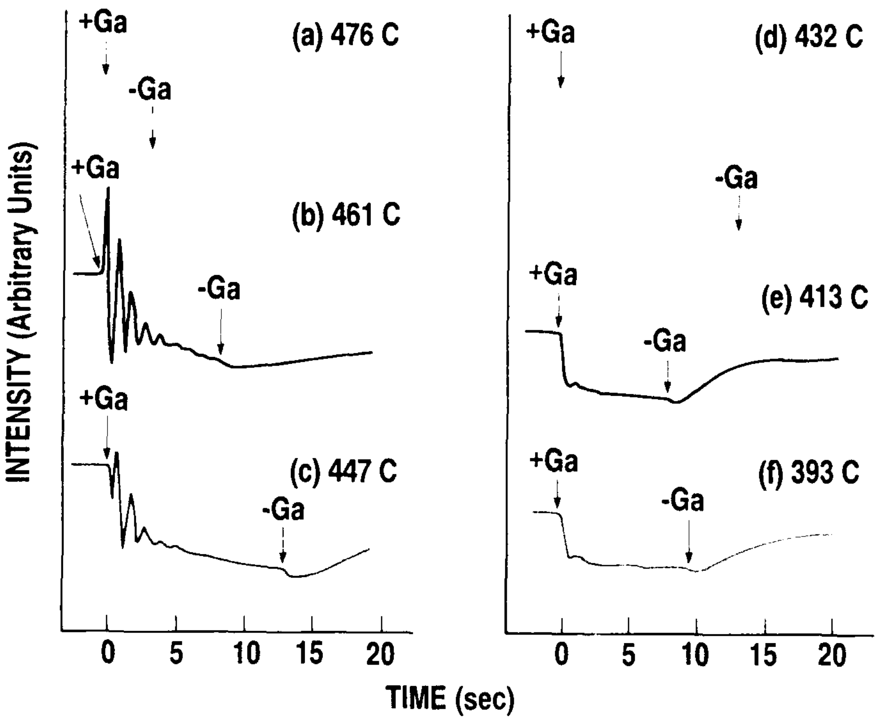


Figure 2. *RHEED intensity oscillations observed during growth of a GaAs (111) epitaxial layer for several growth temperatures. Note the narrow range of temperatures over which oscillations can be observed.*

	Orientation	
	(100)	(111)B
p_{As}/p_{Ga}	10-20:1	5:1
T_{SUB}	500-625 °C	440-465 °C
Growth Rate	0.1-1 μ/hr	1 μ/hr
Surface Reconstruction	(2×4)	Transition

Table 1. *Summarization of reported optimum conditions for epitaxial film growth by MBE for GaAs (111) vs (100).*

A Novel Nonlinear Optical Effect in Liquid-Filled Hollow Core Fibers

Achievement

Scientists at the State University of New York (SUNY) at Buffalo have demonstrated a novel nonlinear optical effect that can transform a monochromatic laser pulse into a multicolored pulse of coherent radiation. The method is ingeniously simple and appears to be highly promising for use onboard airborne or space vehicles where a lightweight, easy-to-service, portable device for simultaneously producing coherent radiation of different wavelengths has many applications.

Figure 1. *Experimental configuration for simulated Kerr scattering measurements using a liquid-core hollow fiber system.*

Background

In this technique, a laser beam is focused into a hollow-core quartz-glass fiber in which the core is filled with certain common organic liquids such as CS_2 or benzene (see figure 1). The high-intensity focused beam interacts with the liquid over a long path length since the beam is confined to the core of the fiber, which has a length of from 0.5 to 5 m and a diameter of from 10 to 100 m. The researchers propose that the high-intensity laser beam and long interaction length cause scattering by the Rayleigh-Kerr and Raman-Kerr effects. In the optical Kerr effect, non-spherical molecules align themselves in a particular orientation to the laser's electric field. This optically induced anisotropic distribution of molecules produces a variation of the refraction index of the medium. Rayleigh and Raman scattering of light in this medium results in a broad-band, quasi-continuous spectrum red-shifted from the pump source. For example, a pump beam from a frequency doubled Nd:YAG laser having a wavelength of 532 nm generates a quasi-continuous spectrum of coherent radiation that can extend to over 1,000 nm into the near IR. A color photograph of a spectrum generated in this fashion is shown in figure 2. This novel technique has numerous advantages over other state-of-the-art methods of producing coherent light simultaneously at multiple wavelengths: (1) the spectral coverage is extremely broad; (2) the medium is nonabsorptive and does not involve problems associated with heat dissipation and thermal decomposition; and (3) the technique works with nanosecond-length laser pulses. The latter is a critical point since the most common continuum generation techniques require picosecond or femtosecond pulses, and rely on self-phase modulation.

Payoff

The knowledge gained in this study has been instrumental in enabling the transition into a Small Business Innovative Research (SBIR) program, which will test the feasibility of this device concept and assess commercial development. If successful, advanced applications in high-speed optical telecommunications that simultaneously require multiple laser wavelengths (e.g., wavelength division multiplexing) would be able to operate with a single laser source instead of an individual laser source for each frequency required.

Contributing Organizations and People

The principal investigator of this effort is Dr. Paras Prasad, director of the Photonics Research Laboratory, SUNY at Buffalo. The program manager is Dr. Charles Lee of the Directorate of Chemistry and Materials Science.

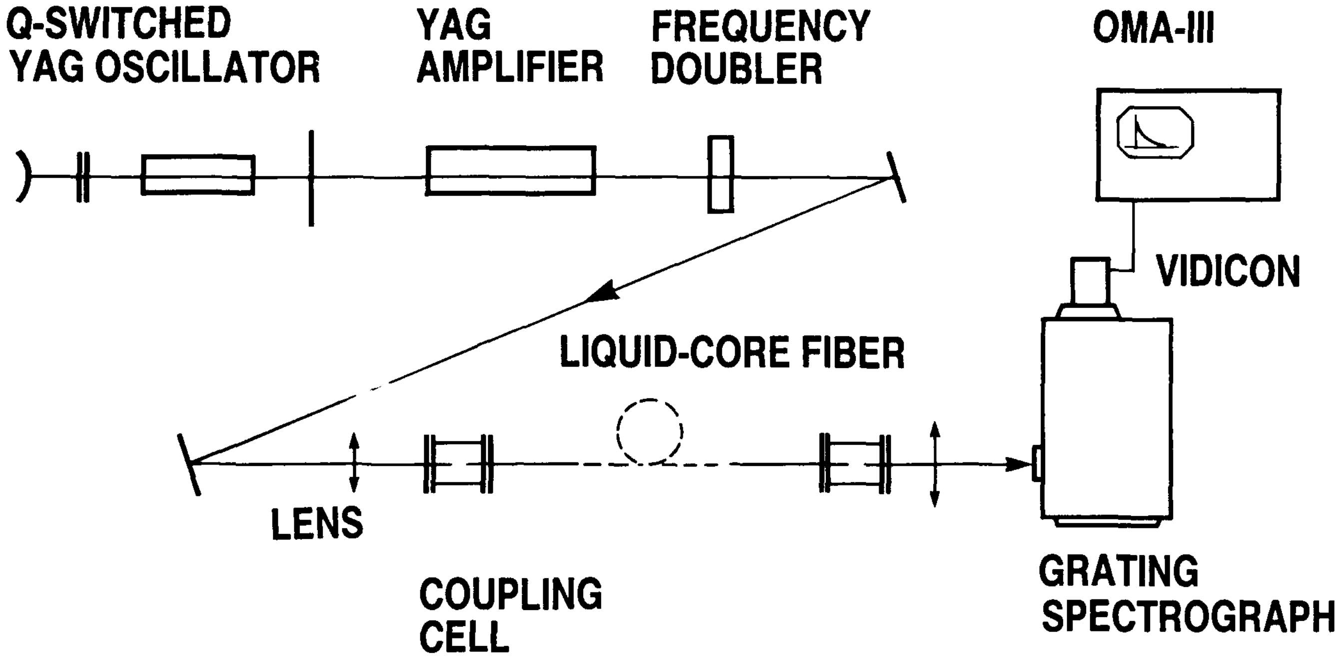


Figure 2. *Nonlinear effects in organic liquid-core hollow fiber.*

Improved Cermets Through Biomimetics

Achievement

An AFOSR-sponsored research effort has resulted in the preparation of a uniquely designed cermet that has exhibited a significant improvement in mechanical properties compared with its conventionally designed analog. Cermets, ceramic-metal composites, are candidate materials for structural applications in high-temperature environments such as turbine engines and NASP airframes. The inspiration for the novel design used for the cermet was the nacre section of the abalone shell. Structural architectures have been optimized through evolution in living organisms over millions of years to provide survival advantages over competing organisms in a given environment. Most of these architectures have been found to be highly sophisticated compared with man-made designs for synthetic materials. The most direct way to use the naturally occurring architecture is to use the material containing the architecture. For many aerospace applications, however, environmental temperatures exceeding 300 °F preclude the use of naturally occurring materials because their chemistry cannot withstand such temperatures. Biomimetics offers a way around this problem. Modeling of the architecture of a natural system such as an abalone shell using temperature-resistant, aerospace-quality, non-natural materials is an example of biomimetics.

Background

The research group involved in this effort at the University of Washington initially carried out an extensive study of the structure of the abalone shell using transmission and scanning electron microscopy. The result of this study was the discovery that the hard part of the shells, called the nacre, consisted of alternating layers of calcium carbonate ($CaCO_3$), approximately 95 percent by volume, and a biopolymeric membrane, approximately 5 percent by volume (figure 1). The membrane has been postulated to play a regulating role in forming the aragonite crystal structure of the $CaCO_3$. Measuring the mechanical properties of the abalone shell nacre revealed that the layered composite design afforded an order of magnitude improvement in both strength and toughness over monolithic $CaCO_3$ (figure 2). This level of strength is comparable to many monolithic ceramics such as aluminum oxide (Al_2O_3), zirconium oxide (ZrO_2), and boron carbide (B_4C), as shown in figure 2. However, in terms of toughness, the nacre is significantly superior. The major mechanisms responsible for the toughness of the nacre were determined to be sliding of the $CaCO_3$ layers on the membrane and bridging of the $CaCO_3$ platelets by ligament formation from the membrane.

Payoff

The strength and toughness exhibited by the layered nacre are much less than can be obtained with the best aerospace-quality cermets such as boron carbide-aluminum (B_4C-Al), as shown in figure 2. In addition, the biopolymeric membrane will denature and decompose at temperatures well below those obtainable with the cermet. It was deduced, however, that the important attribute of the biopolymeric membrane for enhancing mechanical properties was its low modulus relative to the modulus of the $CaCO_3$. Upon analyzing the modulus relationships in the B_4C-Al cermet, it was concluded that the aluminum could be considered a low modulus material relative to the very high modulus B_4C. The usual design of such a cermet consists of a continuous phase of B_4C with aluminum infiltrated into the void regions. To mimic the nacre structure, the B_4C-Al cermet was modified by fabricating it in the form of a laminate with thin layers of aluminum alternating with thick layers of cermet (figure 1). The resultant composite material exhibited a significant improvement in strength and toughness over the un-

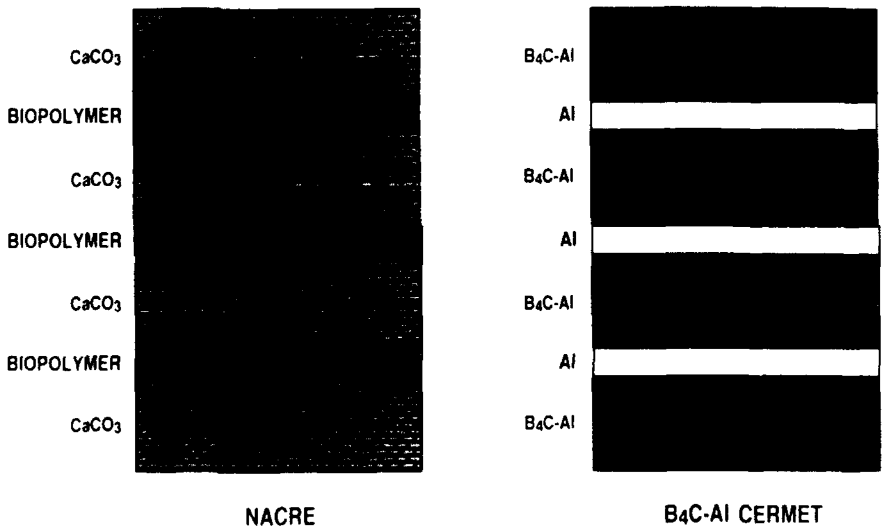


Figure 1. *Layered structure of abalone shell nacre and B_4C-Al cermet.*

modified cermet (figure 2). Both strength and toughness increased 30 to 40 percent.

Contributing Organizations and People

Professors Ilhan Aksay and Mehmet Sarikaya are the leaders of the research effort at the University of Washington. This research is part of a biotechnology initiative in the chemical reactivity and synthesis program at AFOSR, managed by Dr. Fred L. Hedberg of the Directorate of Chemistry and Materials Science. The achievements in this program have been a strong supporting factor in developing a new AFOSR initiative on biomimetics.

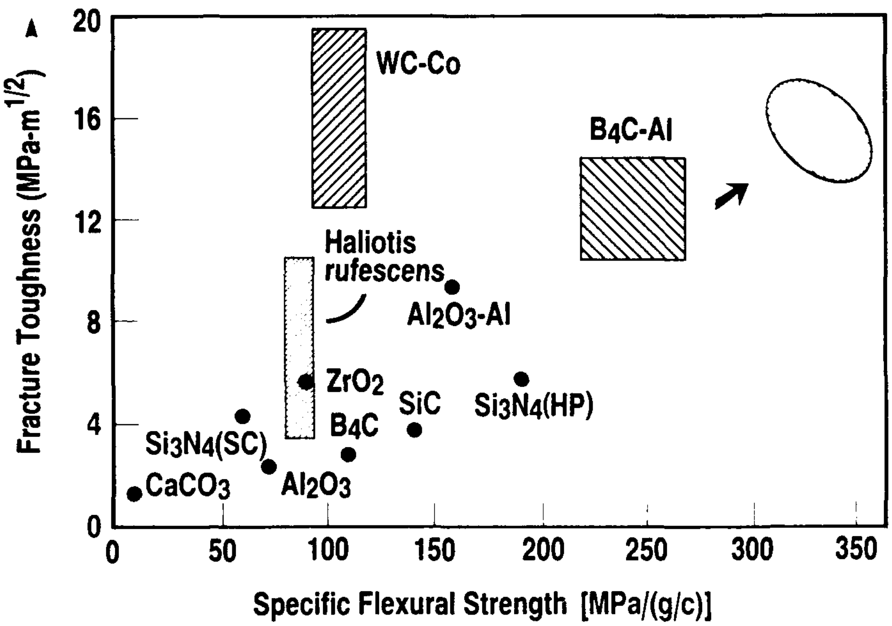


Figure 2. *Strength and toughness values for various ceramics, cermets, and abalone shell (haliotis rufescens).*

Diffusion Barriers in High-Temperature Metal Matrix Composites

Achievement

Reactions of niobium with reinforcements of SiC and Al_2O_3 have been investigated in detail by scientists at the Lockheed Research Laboratory under the sponsorship of AFOSR. Niobium was deposited on SiC and Al_2O_3, and the specimens were heated in vacuum for up to 8 hours in the temperature range of 800 to 1200 °C. Reactions occurring at the interfaces were evaluated using Auger electron spectroscopy (AES), scanning electron microscopy (SEM), and transmission electron microscopy (TEM). Niobium reacted extensively with SiC at temperatures above 900 °C. An example of reaction products forming at 1200 °C after 2 hours is shown in figures 1 and 2 (center). Figure 1 is based upon AES profiles and figure 2 shows TEM microstructural evaluations. However, niobium did not react with Al_2O_3 for times up to 2 hours at 1200 °C. Based on this information, an Al_2O_3 diffusion barrier was selected to minimize interfacial reactions of Nb with SiC. Figure 1 (right) shows an AES profile of a Nb/Al_2O_3/SiC specimen heated to 1200 °C for 2 hours and demonstrates that the 500-nm Al_2O_3 layer is effective as a diffusion barrier. The effectiveness of the diffusion barrier is also demonstrated in figure 2 in which SEM cross-sectional images are shown of similar specimens to those in figure 1. The integrity of the interface region at high temperature is evident in figure 2 (right), and compares quite favorably to the substantially reacted interface region of a similarly heated specimen without a diffusion barrier (figure 2 (center)).

Background

Metal matrix composites based on refractory metals are strong candidates for advanced materials for engines due to their high strength, reasonable modulus of elasticity and good thermal stability. Niobium (Nb) matrix composites are particularly attractive because of their low density and high specific strength. However, reactions occurring at internal interfaces between the Nb matrix and the

- FULL POTENTIAL OF HTMMC IS NOT REALIZED DUE TO INTERFACIAL REACTIONS.
- ONE APPROACH TO MINIMIZE REACTIONS IS INCORPORATION OF DIFFUSION BARRIERS.
- AUGER PROFILING TRACKS INTERDIFFUSION AND REACTIONS AT ATOMIC LEVEL.
- Al_2O_3 FOUND TO BE EFFECTIVE DIFFUSION BARRIER IN Nb/SiC SYSTEM.
- RESULTS PROVIDE SCIENTIFIC BASIS FOR DESIGN OF HTMMC.

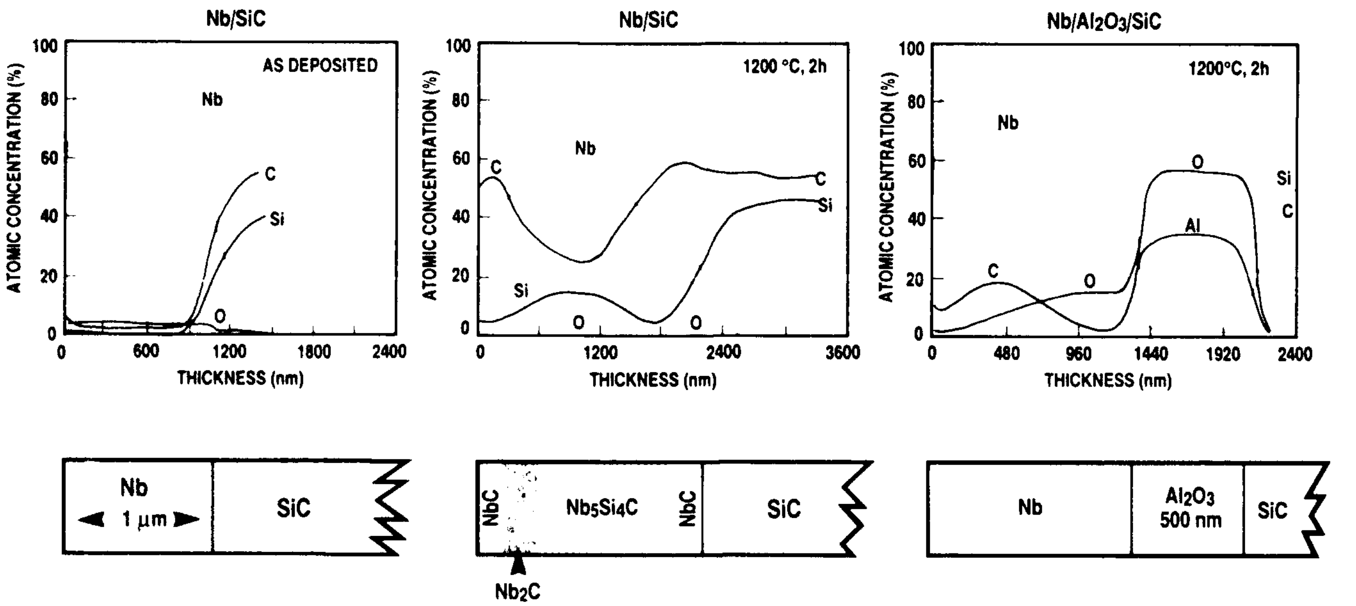


Figure 1. *Diffusion barriers in high-temperature metal matrix composites.*

reinforcement are often found and are undesirable. When the reinforcement is consumed during the reaction undesirable properties result, such as (a) load-carrying ability is lowered; (b) intermetallic phases form and deteriorate mechanical properties and corrosion resistance; and (c) voids and cracks form at the interfaces resulting in an ineffective composite for high-temperature applications. Formation of reaction layers as small as 0.1 micron can be detrimental to composite strength, ductility, and corrosion behavior. This reflects the importance of understanding and controlling the early stages of interfacial reactions.

Payoff

This research could lead to future Air Force engines for aircraft and spacecraft that require advanced materials that maintain exceptional mechanical properties at very high operating temperatures.

Contributing Organizations and People

This research was performed at Lockheed/Palo Alto by Drs. J. Wadsworth and A. Joshi. The program was managed by Dr. Alan H. Rosenstein of the Directorate of Chemistry and Materials Science.

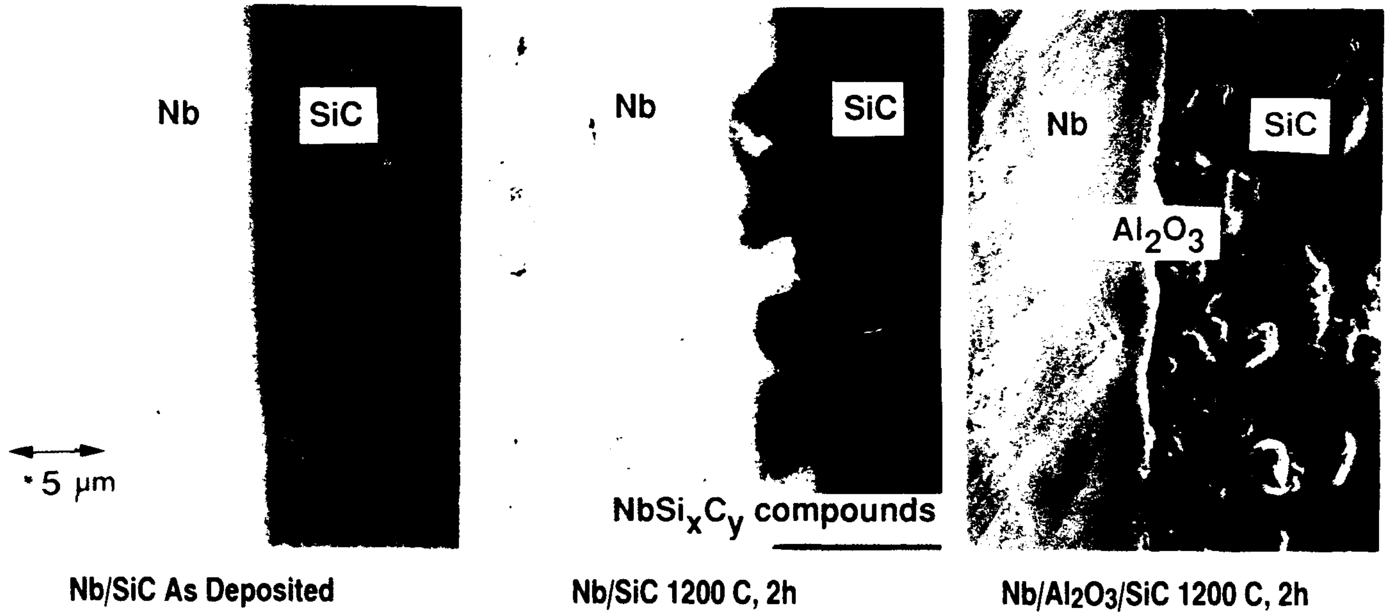


Figure 2. *SEM images of Nb/SiC specimens.*

Nucleation and Growth in Chemical Vapor Deposition

Achievement

Researchers at the Oak Ridge National Laboratory have developed a tool to study nucleation and growth during chemical vapor deposition (CVD). This technique, based on light scattering, can be used as an *in situ,* noninvasive method to monitor the evolution of the surface topography. A wide variety of polycrystalline coatings and thin films can be produced by CVD. Chemical vapor infiltration (CVI), which is CVD in a porous structure, is a related technique that is used commercially to produce composites for high-temperature structural applications. In spite of its technological importance, most of the current understanding of the relationship between the CVD process and the microstructure and properties of the resultant material is qualitative and empirical. Better design and control of CVD materials will be possible with an improved understanding of the nucleation and growth processes that determine the microstructure. The goal of the current program is to understand the nucleation and growth mechanisms during the CVD of polycrystalline materials, using SiC as a model material, and emphasizing *in situ* measurements.

Background

Figure 1 illustrates the light-scattering concept. A He-Ne laser is directed at the substrate surface, and a photodiode array is used to measure the intensity of the scattered light. In theory, the light scattered from the surface contains all the information necessary to characterize the surface topography. As shown, the angular scattering spectrum can be analyzed to obtain a description of the surface profile. The mathematical transforms that are used to accomplish this were first developed to analyze electrical signals, which are typically modeled as Gaussian random processes. These methods are

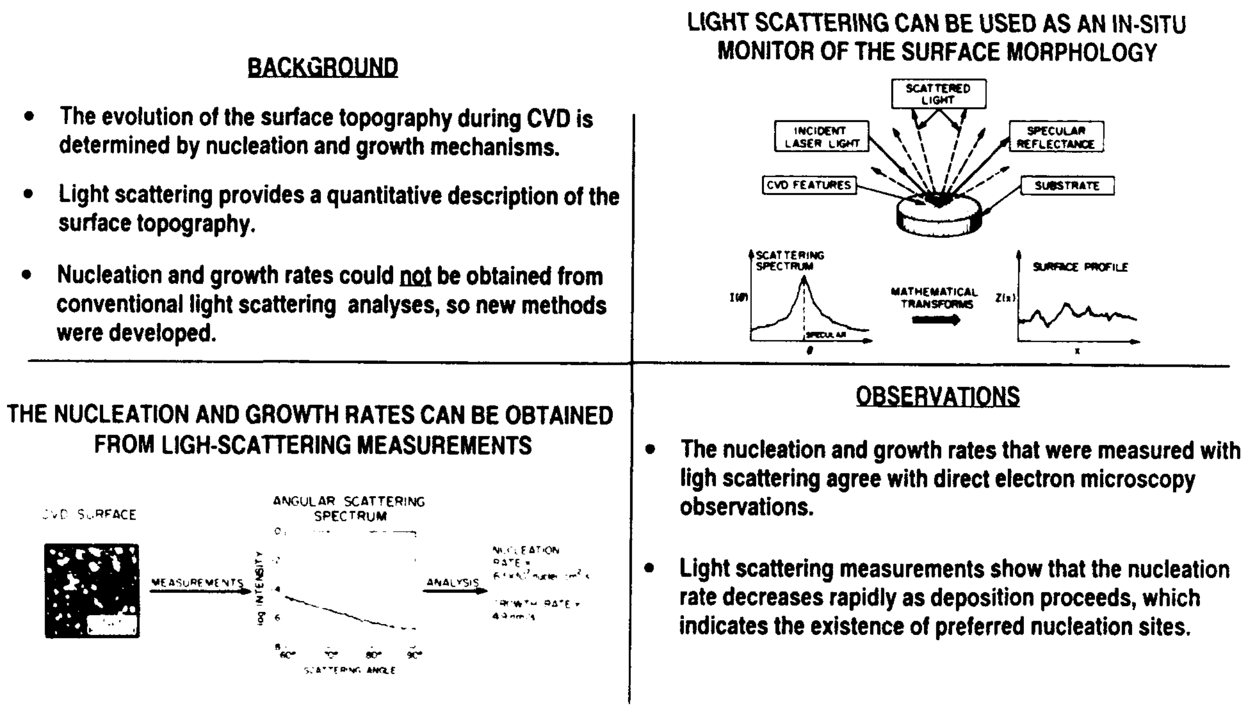


Figure 1. *Light-scattering concept.*

applicable because of the mathematical similarity between a waveform and a surface profile. However, the surfaces that are generated by CVD are not Gaussian profiles, thus the parameters that are obtained from these established methods are semiempirical.

Measuring the size and number density or the submicron surface features provides a more quantitative description of nucleation and growth. Techniques to perform these analyses have been developed, using both numerical Mont-Carlo simulations and analytical shot-noise models to describe the surface topography. Although these methods are an improvement over the standard Gaussian approaches, they do not account for the fact that the actual CVD-generated surfaces consist of a distribution of feature sizes. This distribution is a function of the nucleation and growth rates during deposition. These rates have been measured directly from the light-scattering spectra by incorporating specific nucleation and growth models into a standard shot-noise model.

Experimentally, the light-scattering technique was used to examine SiC surface features that were generated by the CVD of silicon carbide from methyltrichlorosilane (MTS). Using the analytical methods that were developed, the feature sizes obtained from light-scattering measurements agree with the actual feature sizes that were observed by scanning electron microscopy. Figure 2 shows SiC surface features on a polished polycrystalline SiC substrate that were observed after 60 seconds at 3.3 kPa and 1000 °C, with gas flows of 20 cm^3/min of MTS and 2000 cm^3/min of H_2. Image analysis of SEM micrographs of this surface produced a distribution of feature sizes. Comparing this distribution to a model of nucleation and growth on specific surface sites gave a growth rate of 2.0 nm/s and an initial nucleation rate of 1.4×10^5 nuclei/mm^2/s. Analyzing the light-scattering spectrum obtained from this surface with the same nucleation and growth model gave comparable values of 2.1 nm/s for the growth rate and 1.1×10^5 nuclei/mm^2/s for the nucleation rate.

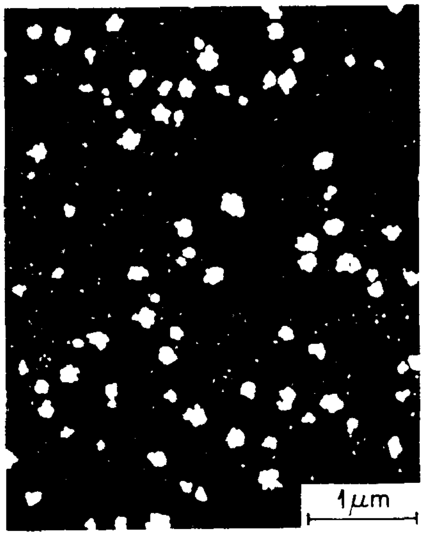


Figure 2. *SiC surface features on a polished polycrystalline SiC substrate.*

Payoff

This light-scattering diagnostic tool is valuable for studying nucleation and growth. It is particularly useful for making *in situ* measurements of the evolution of CVD microstructures; a CVD system with this *in situ* capability has been designed and is currently being constructed and tested. The application of this technique will lead to a better understanding of the microstructure of films deposited on structural substrates. Stealthy thin films or films highly temperature-resistant for engine and reentry applications would greatly benefit from this application.

Contributing Organizations and People

This research was performed by Dr. Brian W. Sheldon and Dr. Theodore M. Besmann of Oak Ridge National Laboratory, as part of a program managed at AFOSR by Lt. Col. Larry W. Burggraf of the Directorate of Chemistry and Materials Science.

DIRECTORATE OF PHYSICS AND ELECTRONICS

Research in this area provides the fundamental knowledge needed to advance Air Force operational capabilities in weapons technology, surveillance, guidance, and control; information and signal processing; and communications, command, and control.

The program is of substantial scientific breadth, extending from quantum physics to the understanding of engineering issues such as electronic or photonic systems performance. This breadth easily leads to opportunities to transfer generated knowledge into Air Force development programs. The nine accomplishments selected this year were chosen for their scientific excellence and because they demonstrate how new scientific knowledge can satisfy military needs.

Spectroscopy of Fundamental Semiconductor Properties

Achievement

Many important material parameters and properties of heterostructures are being studied at the Wright Laboratory through a unique cyclotron resonance spectroscopy system. This technique allows for the investigation of a variety of artificially structured materials such as multiple quantum wells, superlattices, and high electron mobility transistor (HEMT) structures. Direct information about important material parameters has been obtained for GaAs/AlGaAs HEMT and AlGaSb/InAs single quantum well (SQW) structures that will lead to improvements in material performance for specific electronic device applications.

Background

The spectroscopic facility for exploring the magneto-optical behavior of these engineered materials was recently acquired by the Materials Directorate at Wright Laboratory. The system is capable of providing a variety of absorption, transmission, and photoconductivity measurements on virtually any bulk or layered film samples.

The main research focus is currently directed at thin film semiconductor microstructures such as HEMTs and SQWs. The system includes a high-resolution Fourier Transform Infrared (FTIR) spectrometer and three variable-temperature cryostats, one of which contains a 7 Tesla split coil superconducting magnet. The basic capabilities of the system are as follows:

Wavelength range - 10 to 22,000 cm^{-1} (0.5 to1000μm)

Maximum resolution - 0.0026 cm^{-1}

Temperature range - 1.7 K to 300 K

Magnetic field range - 0 to 7 T

In the short time during which this spectroscopy system has been in operation, several studies involving various heterostructures have been initiated. One study concerns the far-infrared cyclotron resonance (CR) spectra of an AlGaSb/InAs SQW structure. An example of one of the results obtained is shown in figure 1. This figure illustrates how the CR spectrum changes as a function of magnetic field (B) for the two-dimensional electron gas (2DEG) formed in this SQW.

In the presence of a magnetic field, the electronic level(s) in the well will split into a series of Landau sublevels. An electronic transition between the highest occupied and lowest vacant sublevels can be photo-induced, giving rise to a CR transmission peak for each magnetic field value as shown in figure 1. The energy position of this peak, which is the energy separation between neighboring Landau levels, is a function of the strength of B and the effective mass of the electrons in the levels. Notice in this figure how the peak position shifts to higher energy (larger wavenumber) as B is increased. This is expected because the Landau level (LL) splitting becomes larger as the field increases. In addition, cyclic variations (i.e., oscillations) of the CR spectrum amplitude and full width at half maximum (FWHM) are observed as a function of B as shown in figure 1. Further analyses of the CR spectra indicate that the effective mass of the charge carriers as well as the scattering time of the 2DEG exhibit

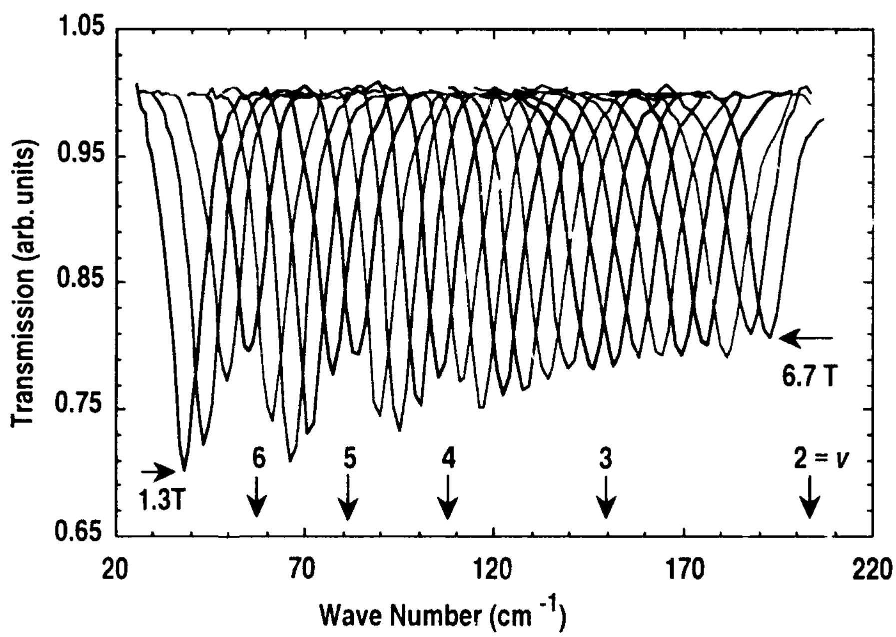


Figure 1. *Far-infrared cyclotron resonance spectra of the 2DEG in $Al_{0.6}Ga_{0.4}Sb/InAs/Al_{0.6}Ga_{0.4}Sb$ taken in the magnetic field range of 1.3–6.7 T at intervals of 0.2 T. Sample temperature = 4.2 K. The vertical arrows indicate integer filling factors (ν) of LL's. Notice that the minima in the amplitudes of the CR spectra correlate very well with ν. The sample was grown by MBE at Wright Laboratory.*

oscillatory behavior similar to that of the amplitude and FWHM. The oscillatory behavior of various CR parameters was found to correlate with integer filling factors (v) of LL's, which are shown in figure 1 as the vertical arrows. It should be pointed out that integer filling factors mean that the corresponding LL's are completely full. Based on the correlation between v and CR parameters, one can explain the above oscillatory behavior in terms of electron-impurity interactions and screening effects.

Payoff

Advanced Air Force weapons and communications systems require high-speed computing and signal processing capabilities. Improving and developing compound semiconductor materials and structures will provide unique opportunities for advances and applications in high-speed signal processing, communications, and surveillance. Thin film semiconductor heterostructures are assuming increasing importance in electronic and opto-electronic devices because they can be designed, or bandgap engineered, for optimum performance. However, full exploitation of their potential requires detailed knowledge of the 2DEG formed at the interfaces and knowledge of the resultant materials' band structures.

Contributing Organizations and People

This research is being performed as a cooperative venture between Mr. D. W. Fischer of the Materials Directorate and Dr. M. O. Manasreh of the Solid-State Electronics Directorate, Wright Laboratory. It is part of a program managed by Dr. Horst R. Wittmann and Maj. Gernot S. Pomrenke of the Directorate of Physics and Electronics.

High-Temperature Superconductor Films

Achievement

A collaboration of Stanford University and Xerox Palo Alto Research Center scientists has produced exceptionally high-quality, technologically relevant films of yttrium barium copper oxide (YBCO), a so-called high-temperature superconductor (HTS), in proximity to silicon substrates. These films were grown epitaxially on silicon wafers with the aid of a buffer layer of yttria-stabilized zirconia (YSZ) using a fully *in situ* pulsed laser deposition process. This sandwich-like combination of a superconductor and a semiconductor (figure 1) represents an important first step in coupling semiconductor microelectronic devices with the unique capabilities of superconductors to provide a hybrid class of devices with superior performance and new capabilities. Previously, many research groups worldwide had attempted without success to produce such high-quality films on substrates that could be of practical value in microwave and other high-frequency circuitry.

Background

The high quality of the films produced (comparable to the most favorable values reported for films on

DEPOSITION

- **Pulsed Laser**
- **YBCO**
- **YSZ buffer layer**
- **Silicon substrate**
- **Ordered Epitaxial Growth**

CHARACTERISTICS

- **High T_c of 86 K**
- **High j_c of 4.6×10^6 A/cm^2 at 77 K**
- **Low microwave surface resistance**
- **Low noise at T_c**

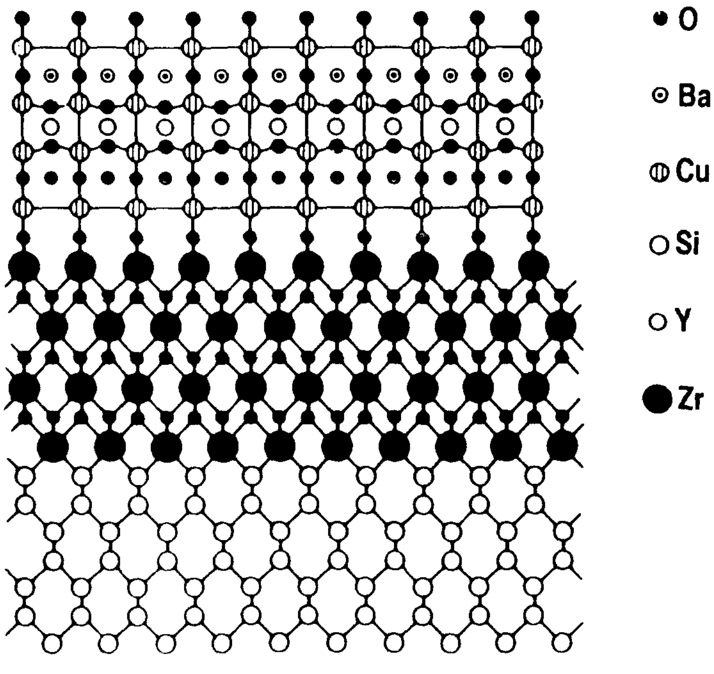
APPLICATIONS

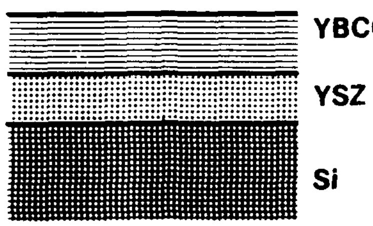
- **Low noise, sensitive IR detector**
- **Passive microwave components**
- **Hybrid supercon/semicon circuits**

AFOSR CONTRACTORS

- **Xerox Palo Alto Research Center**
- **Stanford University**

Crystal Structure





Layer Structure

Figure 1. *Schematic representation of the epitaxial growth of high-quality, superconductive YBCO on a substrate of silicon, with an intermediate buffer layer on YSZ. Grown by a unique laser-deposition system, this composite film of a superconductor and a semiconductor is the starting point for a new generation of hybrid electronic devices.*

$SrTiO_3$ and MgO, two substrate materials with superior lattice matching but with undesirable dielectric properties) is exemplified by their high critical-current density, e.g., in a 30-nm thick film this was found to be $2x10^7$ A/cm^2 at 4.2 K and $2.2x10^6$ A/cm^2 at 77 K, as well as by a zero-resistance critical temperature of about 87 K, superconducting transition width of 1 K, and a relatively low room-temperature (300 K) resistivity of 0.28 mOhm-cm. X-ray diffraction scans further indicate good in-plane, epitaxial alignment, within one and two degrees for the YSZ and YBCO respectively.

The pulsed laser ablation deposition system uses a unique 10-sided polygon target holder that has an equal number of hot-pressed targets on its faces, and is rotated to provide ablation pulses (produced by a 308-nm XeCl excimer laser) at a frequency between 1 and 10 Hz. Additionally, the deposition system features a N_2-purged glove box and a load lock to introduce hydrogen-terminated silicon wafers, and it has a water-cooled shroud to reduce heating from the substrate heater.

Hybrid superconducting-semiconducting devices may be as simple as the application of superconducting interconnects to semiconductor and normal metal circuit elements, or they may be far more complex, involving monolithic integration of HTS devices onto semiconductor wafers containing conventional VLSI CMOS circuits or even devices that rely on the specific interplay between the electronic properties of superconductors and semiconductors.

Payoff

Both active and passive superconductive electronic devices are expected to find application in Air Force systems relating to IR detection and microwave reception. Superconductive components generally operate at higher speed with lower noise and dissipation of power than do semiconductor and metallic components. These more desirable qualities are especially welcome in aerospace systems that require almost instantaneous sensing and signal processing in a compact package. Until recently, the only known superconductors that could be used for such operations could do so only at very low temperatures that could be obtained only in the presence of liquid helium. The increased size and power required, as well as problems relating to the long-term reliability of refrigeration units, had diminished interest in the use of superconductive electronics for aerospace applications. With the evolution of a new superconductive thin-film technology that can operate effectively at temperatures requiring only liquid nitrogen, superconductivity-based electronics becomes a more viable alternative for higher performance aerospace systems.

Contributing Organizations and People

This research was carried out primarily at the Xerox Palo Alto Research Center under the direction of Dr. Neville Connell and Dr. James Boyce, with partial support provided by an AFOSR contract. A major contribution to this effort came from David Fork, a Ph.D. candidate at Stanford, where the research was supported primarily by AFOSR funding. Both of these AFOSR research programs are managed by Dr. Harold Weinstock of the Directorate of Physics and Electronics.

Novel Microwave Power Device

Achievement

A new record for microwave power output from a GaAs field effect transistor (FET) has been demonstrated by a team at MIT/Lincoln Laboratory. The device incorporates a novel insulating layer, an earlier discovery of the team.

Background

For many microwave or millimeter wave power applications, the device of choice is a three-terminal structure known as an FET. For higher frequencies, compound semiconductor materials such as GaAs or indium phosphide (InP) are chosen for their performance advantage over the more common silicon. InP FET's have shown the highest power output density for any material. However, InP materials and device technology are much less mature than for GaAs, and, particularly, for silicon. Thus, there is considerable interest in finding a GaAs high-frequency device that offers performance comparable to InP.

The diagram, figure 1, shows the multiple-layered structure used in the device. The novel aspect of the design is the use of thin layers of "low-temperature" (LT) GaAs. Here, LT refers to GaAs grown via MBE at extremely low growth temperatures. This material has recently been shown to have remarkable structural, electronic, and optical properties.

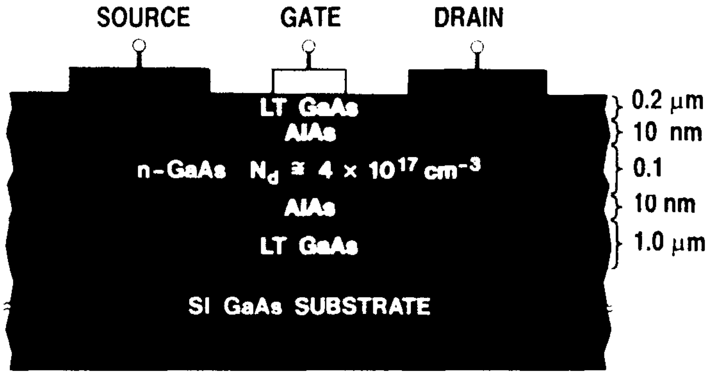
This first application demonstration for LT material was the near-elimination of backgating in digital and analog GaAs circuits. The lower LT GaAs layer in the device diagram is for this purpose. The new application in this device is the LT layer beneath the gate contact. This insulating layer produces a MISFET (metal-insulator-semiconductor) device. The effect of this layer is to increase the gate-drain breakdown voltage from 15 V (without the LT gate layer) to over 40 V. It also leads to the higher output power density. The measured power density at a frequency of 1 GHz is 1.57 W/mm. In comparison, the best reported commercial GaAs FET figure is 1.4 W/mm. The best silicon MISFET result is 0.3 W/mm. The corresponding value for an InP FET is 4 W/mm. Other performance figures-of-merit such as transconductance, gain, and power-added efficiency equal or exceed the values for conventional GaAs structures.

These results are based upon early, unoptimized devices. Efforts are currently underway to redesign the structure for higher frequency operation. The same device is promising for microwave switching applications due to the low gate capacitance, low channel resistance, and high breakdown voltage.

Payoff

Such devices promise rapid application to a variety of Air Force electronics

STRUCTURE



ADVANTAGES

- HIGH BREAKDOWN VOLTAGES
- ABILITY TO HEAVILY DOPE THE CHANNEL AND FORWARD BIAS GATE PROVIDES
  - THE HIGH CURRENT
  - LOW ON-RESISTANCE
- LOW SUBSTRATE LEAKAGE
- LT GaAs INSULATOR PROVIDES LOWER AND MORE CONSTANT GATE CAPACITANCE
- COMPATIBLE WITH CONVENTIONAL PLANAR TECHNOLOGY

OUTPUT POWER DENSITY = 1.57 W/mm

Figure 1. *Low-temperature GaAs MISFET*

systems requiring high-frequency solid-state power sources. In particular, this device is predicted to revolutionize the power modules in phased arrays and similar applications. It will be possible to achieve higher powers and higher frequencies within a smaller volume, while improving frequency agility.

Contributing Organizations and People

The research was performed at MIT/Lincoln Laboratory by a team headed by A.R. Calawa and Frank Smith. The program was managed by Dr. Gerald Witt of the Directorate of Physics and Electronics.

High-Performance Gallium Antimonide-Based Devices

Achievement

Researchers at Columbia University working with new semiconductor materials have produced a device with extremely superior transport properties. The group studied and demonstrated the first p-channel gallium antimonide (GaSb) modulation-doped field-effect transistor (MODFET). The research has the potential to significantly affect complementary logic integrated circuits based on compound semiconductors.

Background

The Air Force continues to require electronic materials and devices with improved performance characteristics such as those based on III–V compound semiconductors. In the case of the technologically important gallium arsenide (GaAs) III–V semiconductor, the electron mobility is 10 times that of silicon; however, the hole mobility is lower. As a result, the performance of GaAs-based complementary circuits is limited by the p-channel device. To address this performance limit of GaAs and also aluminum gallium arsenide (AlGaAs), the GaSb p-channel FET's were investigated due to the superior hole transport properties.

The hole mobility of GaSb (850 cm^2/V-s) is more than twice the value of GaAs (400 cm^2/V-s). Furthermore, a large valence band offset exists between the GaSb channel and AlSbAs barrier layer, which reduces gate leakage and allows thinner barrier layers to be used. These factors assist in minimizing static power dissipation and further increase the performance over GaAs-based complementary circuits.

To study these devices, structures were grown by MBE on InP semi-insulating substrates. As shown in figure 1, a typical structure consists of a GaSb/AlSb superlattice layer (SL), and an aluminum gallium antimonide (AlGaSb) buffer layer, a GaSb channel, and an $AlSb/AlSb_{0.9}As_{0.1}$ barrier layer, and finally a GaSb layer for passivation. $AlSb_{0.9}As_{0.1}$ was employed as a part of the barrier layer since the addition of arsenic (As) to AlSb further increases the valence band offset to GaSb and improves the gate contact characteristics. The AlSb layer

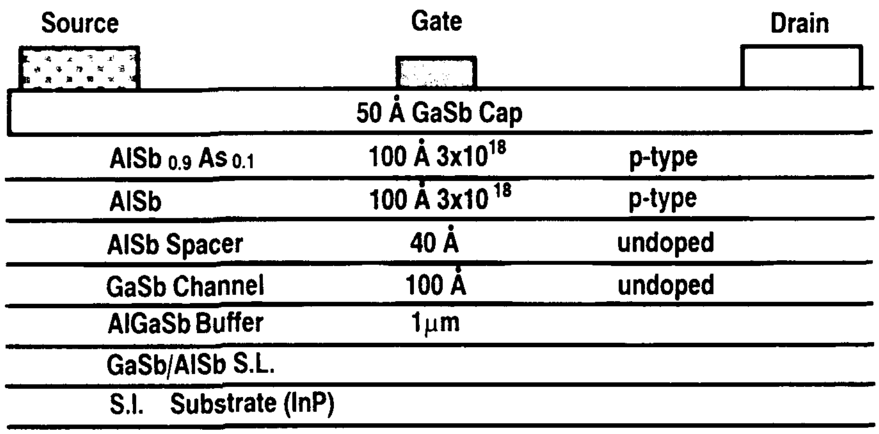


Figure 1. *Schematic cross-section of GaSb p-channel MODFET.*

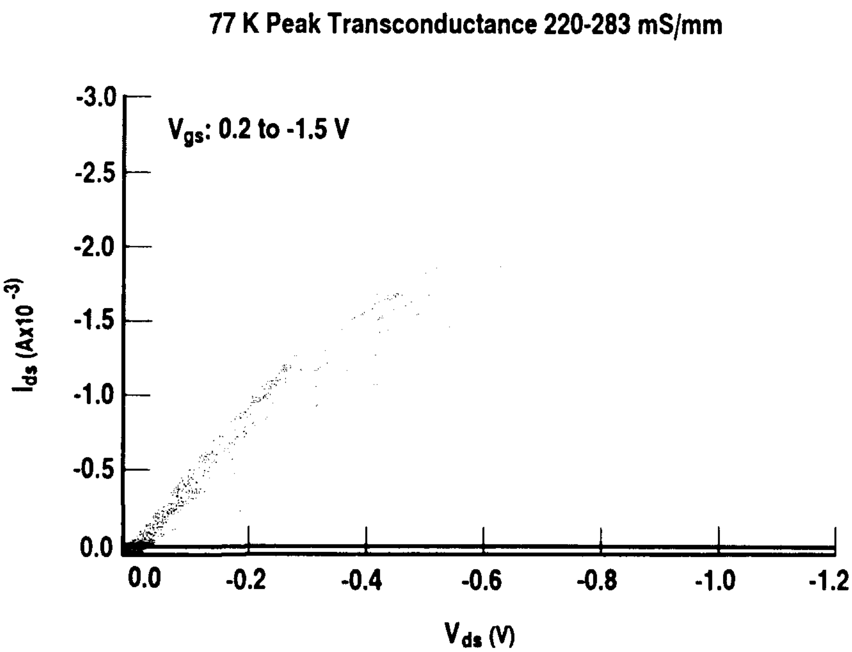


Figure 2. *Output characteristic of the transistor at 77 K.*

adjacent to the channel improves the channel interface quality and thus the transport in the channel.

Conventional FET processing was employed to fabricate the devices, and mesas were defined by wet chemical etching. Devices of 1–μm gate length exhibit transconductances at a temperature of 77 K in the range of 220 to 283 mS/mm as demonstrated in figure 2. These represent the highest transconductances of any compound p-channel heterostructure FET published to date and demonstrate the superior transport properties of the GaSb channel. (The transconductance is a device measure of the change in drain current resulting from a change in voltage in the gate circuit.) In addition, the devices exhibited gate leakage currents that when measured at 77 K are three orders of magnitude lower than the maximum drain saturation current.

Payoff

Thus, GaSb p-channel MODFET's with a high transconductance and low-gate leakage have been demonstrated. These devices could be integrated with indium arsenide (InAs) device structures to form a complementary circuit technology based on InAs/AlSb/GaSb. The superior transport properties of electrons in InAs and holes in GaSb and their band offsets to AlSb or AlSbAs make this possibly the ultimate performance III–V semiconductor-based complementary heterostructure FET. This research has the potential of substantially increasing the speed and reliability of future Air Force computer and communication systems.

Contributing Organizations and People

This research program was performed by a group at Columbia University headed by Professor W.I. Wang. The program was managed by Maj. Gernot S. Pomrenke of the Directorate of Physics and Electronics.

Rigorous, Simple Measure of Laser Beam Quality Introduced and Applied

Achievement

An important new concept, the so-called M^2 factor, has been conceived and studied to define and measure the quality of a laser beam. The availability of this concept, together with relatively simple measuring instrumentation, makes it possible to compare performance of different laser systems in a meaningful way, and also makes possible improved performance tuning of laser devices and more reliable design of laser beam transmission systems.

Background

The ability to put laser energy on a target depends critically on the quality of the laser beam (figure 1). Despite this, there has not been, in the past, a simple parameter that could characterize and compare the quality of different laser beams. A variety of parameters have been commonly used to describe laser beam quality. Although they are sometimes helpful, they are ambiguous in definition, and quite often give very misleading results (figure 2). The M^2 factor, in contrast, provides a unique and meaningful way to characterize and compare laser beams.

The M^2 factor is defined in terms of the variance of the intensity distribution, σ_r across the beam and the variance of its angular spread, σ_p*. Both of these quantities can be rigorously defined and calculated for any real laser beam. The studies show that, for free space propagation, the intensity variance has a minimum value, σ_{ro} (analogous to the beam "waist" for an ideal Gaussian beam), and the angular variance is a constant. Further, it can be shown that, for any beam, the product $\sigma_{ro}\sigma_p$ is always equal to or greater than $1/2\pi$, and equal when the beam is an ideal Gaussian beam. The M^2 factor is defined as the space-beamwidth product, ($\sigma_{ro}\sigma_p$ relative to the space-beamwidth product) for an ideal, Gaussian beam, and is therefore $2\pi\sigma_{ro}\sigma_p$. M^2 thus has the convenient property that it is equal to one for a true, Gaussian mode beam, and is always greater than one for a less than ideal beam.

Payoff

The quality of laser beams used in Air Force systems such as target designators, rangefinders, illuminators, communicators, and potentially, as weapons, is vitally important to the system performance. The ability to define and directly measure a simple but unique and rigorous single parameter of quality will lead to dramatic improvements in characterizing existing systems and developing future ones.

The M^2 factor has a number of important features that make it a uniquely practical and useful measure of laser beam quality. It is

(a) rigorously definable even for irregular or multimode laser beams, yet is simple in concept;

(b) meaningful for characterizing both far-field beam spread and higher order mode content of a laser beam;

(c) useful as guidance for designers of optical beam trains and focusing systems for a laser system;

(d) easy to measure on real laser systems; and

(e) easy to use in optical system design calculations.

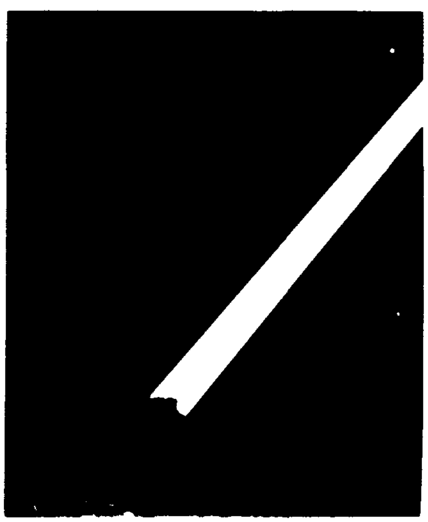


Figure 1. *The ability to put laser energy on a target depends, vitally, on the quality of the laser beam.*

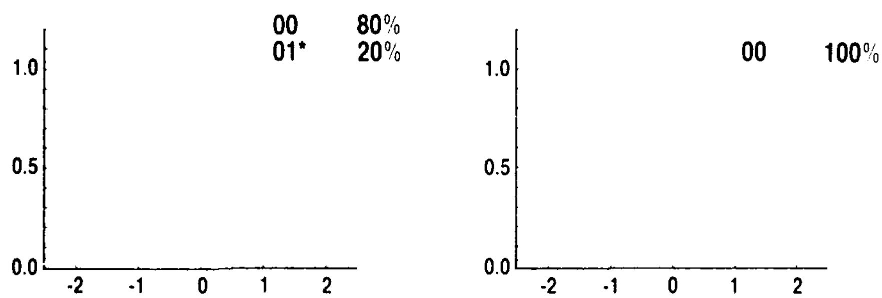


Figure 2. *M^2 meter dramatically illustrates that small changes in laser tuning, leading to imperceptible changes in appearance of the output beam, can result in large, sudden changes in beam quality.*

The rigorous definition of M^2, and the relationships derived for it and its associated variances, have led to the development of a commercial instrument, an "M^2 meter," for displaying directly the value of M^2 for a continuous wave beam impinging on it. The development and its commercial sale represents an important example of university/industrial technology transfer. Use of the M^2 meter can dramatically illustrate its importance, demonstrating directly that small changes in laser tuning, leading to imperceptible changes in the appearance of the output beam, can nonetheless result in large, sudden changes in beam quality (figure 2).

Contributing Organizations and People

The conception and study of the M^2 concept was conducted by Professor Anthony E. Siegman of Stanford University, together with Drs. Tom Johnston and M.W. Sassnett of Coherent Corporation, which is marketing the CW beam-measuring instrument. Research is underway in Professor Siegman's laboratory to develop an instrument that can display M^2 from a pulsed laser, measured from a single input pulse. The AFOSR program manager is Dr. Howard Schlossberg of the Directorate of Physics and Electronics.

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* *For very astigmatic beams it is useful to define M^2 and its associated variances separately for two perpendicular axes along the beam.*

Entire Visible Spectrum Produced From Single Laser Spectral Component

Achievement

Recent work performed at the Phillips Laboratory Center in nonlinear optics in fibers has produced spectral components that cover the entire visible spectrum from a single injected spectral component.

Background

The process that generates these frequencies is phase-matched four-wave mixing. The researchers launch 532-nm Q-switched pulses down a multimode fiber and observe phase-matched four-wave mixing. This process involves the absorption of two green (532 nm) photons and the emission of a blue (440 nm) photon and a red (640 nm) photon. The process is not observed in a single-mode fiber, indicating that transverse modes of the fiber are necessary to satisfy the phase-matching conditions. Figure 1 shows the relative angles of the wave vectors of the three fields involved in the process.

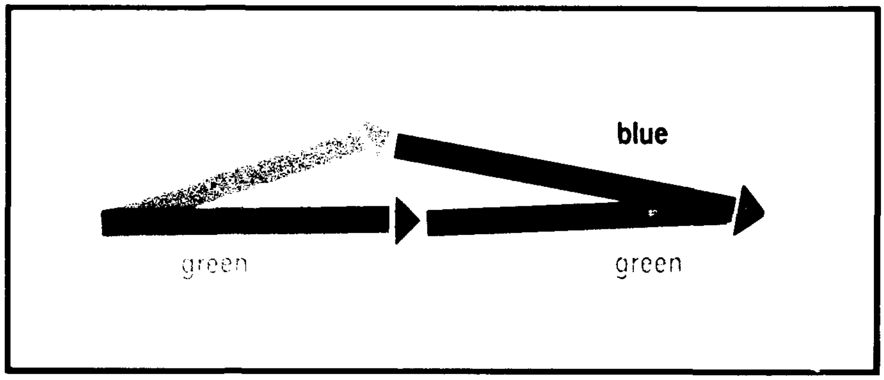


Figure 1. *The wave vectors of the three wavelengths involved in the phase-matched four-wave mixing process observed in optical fibers.*

Payoff

Optical fibers provide an excellent medium for studying nonlinear effects since they can obtain large intensities over long interaction lengths. In addition, they are inexpensive and physically robust compared with typical nonlinear crystals. This nonlinear phenomenon can conveniently shift the frequencies of available sources to spectral regions more appropriate for specific applications (e.g., atmospheric transmission windows, infrared detection electronics). The process is also important in fiber-optic communication, increasing the capacity of information transmission by using a number of wavelength bands. In addition to these applications, the phenomenon might also be used in a compact color display.

Contributing Organizations and People

This work was performed at the Phillips Laboratory Center for Nonlinear Optics by Dr. Karl Koch. The program was sponsored by AFOSR, and managed at the Phillips Laboratory by Dr. Chris Clayton and at AFOSR by Dr. Howard Schlossberg of the Directorate of Physics and Electronics.

New Computational Methods Provide Dramatic Supercomputer Performance Improvements for Many Air Force Applications

Achievement

With the development of the ACES (Advanced Concepts in Electronic Structure) program system, there has been a major advance both in theory and in computational methods for calculating the electronic structures of molecular systems. These programs are based on the highly accurate coupled-cluster (CC) and many-body perturbation theory (MBPT) methods, which add the essential effects of electron correlation onto an SCF (self-consistent field) or other single determinant starting point. The CC and MBPT methods are the result of extensive theoretical research.

The improvement in program performance has been dramatic. ACES II, which permits CC/MBPT calculations with up to about 250 functions, performs at factors of 10 to 500 (depending on molecular symmetry) faster than the well-known and widely used Gaussian 90 program. One supercomputer can now be used to perform calculations that would previously have required 10 to 500 supercomputers. Furthermore, ACES II is the only program that allows the use of general contracted Gaussian functions in the evaluation of CC/MBPT analytical gradients (important for applications in nonlinear optics).

Background

ACES was initially written for scalar, small-memory machines, and even though it evolved into a CRAY supercomputer version, certain essential elements in the program structure were inappropriate to the CRAY environment. An observation of how to organize the CC equations in terms of the minimum set of intermediates and how to efficiently incorporate Abelian symmetry into CC/MBPT applications led to the production of an entirely new version, ACES II, directed toward vector machines like the CRAY YMP.

Payoff

ACES II is currently being installed on the CRAY supercomputer at the Air Force Weapons Laboratory, where it will be used by Air Force scientists and contractors in applications such as high-energy density materials (searching for candidate systems for unusual means of energy storage), nonlinear optical properties of materials (for frequency multiplication of laser radiation, laser designator applications, and explaining the optical properties of the atmosphere), and plume detection and identification (obtaining information on rocket plume interactions with the atmosphere for detection and sensor design).

Contributing Organizations and People

The CC theory and MBPT methods and the ACES computer programs based on them are the work of Professor Rodney J. Bartlett and his colleagues in the Quantum Theory Project at the University of Florida. The AFOSR program manager is Dr. Ralph E. Kelley of the Directorate of Physics and Electronics.

Fast-Recovery, High-Speed, High-Power Switch for Impulse Radars and High-Power Microwave Weapons

Achievement

A fast-recovery subnanosecond switch is being developed by the Air Force Phillips Laboratory. Models have been tested at power levels ranging from 250 MW to well over 1 GW.

Background

The switches are of the high-pressure gas breakdown type, and have been operated at over 1,000 pulses per second for over 1 second with no gas flow. Very rapid forward voltage rates, exceeding 10 TV/sec, are achieved with resonant air core transformers. A new low-inductance design is anticipated to handle over 10 GW and show significant reduction in electrode erosion. One of these devices is shown in figure 1.

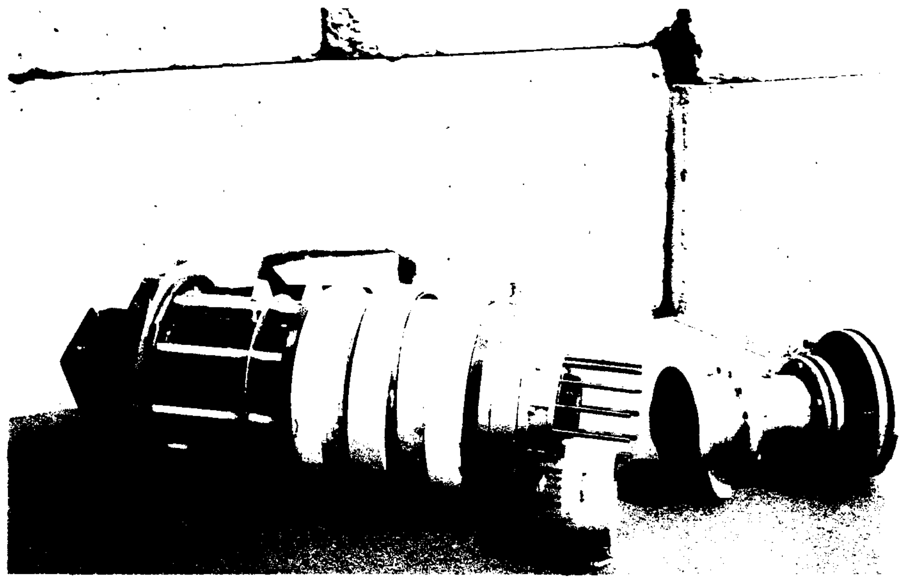


Figure 1. *Experimental 10 cm switch. The housing on left holds charging and triggering controls. The center cylindrical collar provides the high-pressure housing and diagnostics. The housing on right connects current to load. The electrodes can be seen inside the black rings between the left and right housings.*

Payoff

Future work will concentrate on using high-pressure hydrogen. A goal of TW power levels, at 10,000 pulses per second, with subnanosecond rise times appears reachable. The device has application to Air Force needs in impulse radar and high-power microwave weapons.

Contributing Organizations and People

The work was accomplished by Richard P. Copeland and James P. O'Loughlin of the Phillips Laboratory, WSES, Kirtland AFB, NM. The AFOSR program manager is Lt. Col. James A. Lupo of the Directorate of Mathematical and Computer Sciences.

DIRECTORATE OF LIFE AND ENVIRONMENTAL SCIENCES

We learned a lot of important lessons from Operation Desert Storm. One was how important the environment is in determining how well the Air Force can get its job done. A second major lesson was how important well-trained people are in ensuring the success of the mission. The directorate's concern is to provide the fundamental knowledge required to understand and predict the nature of the aerospace environment, to improve the performance of those who must conduct demanding missions in this environment, and to protect those individuals and the environment from the chemical and physical hazards to which they are exposed. We manage a number of programs in the atmospheric, space, and terrestrial sciences, as well as in the biological and behavioral sciences, that are providing new approaches to these concerns. We can highlight only a few of the most recent accomplishments of these programs here.

Research in atmospheric sciences is providing fundamental information about the dynamic changes in the physical and chemical characteristics of the mid- and upper atmosphere required to improve models used for numerical weather prediction. An exciting new technique designed to detect charge buildup in clouds and thus predict potentially damaging lightning strikes is discussed in the following pages.

One of the main thrusts of the space environment program is examining the influence of solar activity on the physical and chemical dynamics of the magnetosphere and the interaction of the magnetosphere with terrestrial and ionospheric processes. We demonstrate here how improved understanding of these interactions and their consequent energy transfer has resulted in improved space weather prediction.

Research in bioenvironmental sciences lays the foundation for understanding how the various physical and chemical agents used in Air Force operations interact in harmful ways with both humans and the environment. Such understanding is resulting in the development of new techniques to prevent contamination of the environment, such as the microbial technique described herein.

Research in cognition, neurosciences, and chronobiology is exploring the links between biochemical and physiological processes of the brain and the ultimate behavior of the organism. These studies will determine how well individuals can handle demanding situations that involve jet lag, stress, fatigue, and sleep disruption. Two examples describe how basic research may lead to novel strategies to maintain and improve human performance during demanding Air Force operations, like Desert Storm, that require sustained operations, transmeridian travel, shift work, and night/in-weather operations.

Our research programs in sensation and perception, computational neuroscience, learning abilities, and intelligent training are making major contributions to speech recognition, visual displays for cockpits and simulators, and the development of new paradigms for the important task of training Air Force personnel. Many accomplishments from these important programs were highlighted in the 1989 and 1990 editions.

We have a dynamic research program in the life and environmental sciences that is conducted by integrated teams of scientists from Air Force laboratories, academia, and industry to address the research needs of the Air Force. This booklet provides just a snapshot of the program. Contact the appropriate program manager for additional details.

Cognition—The Limiting Factor in Air Force Systems

Achievement

The interdisciplinary team of neuroscientists and engineers at EEG Systems Laboratory, San Francisco, directed by Dr. Alan S. Gevins, has focused on developing and applying algorithms and software to measure fundamental neurocognitive processes such as attention, memory, language, and visuomotor function. These processes are measured by recording brain waves from up to 124 sites on the scalp. This is the first time the measuring of these processes has been successfully accomplished by any researcher. Novel signal processing algorithms then extract neurocognitive patterns from these data in split-second time intervals corresponding to the mental stages of task performance.

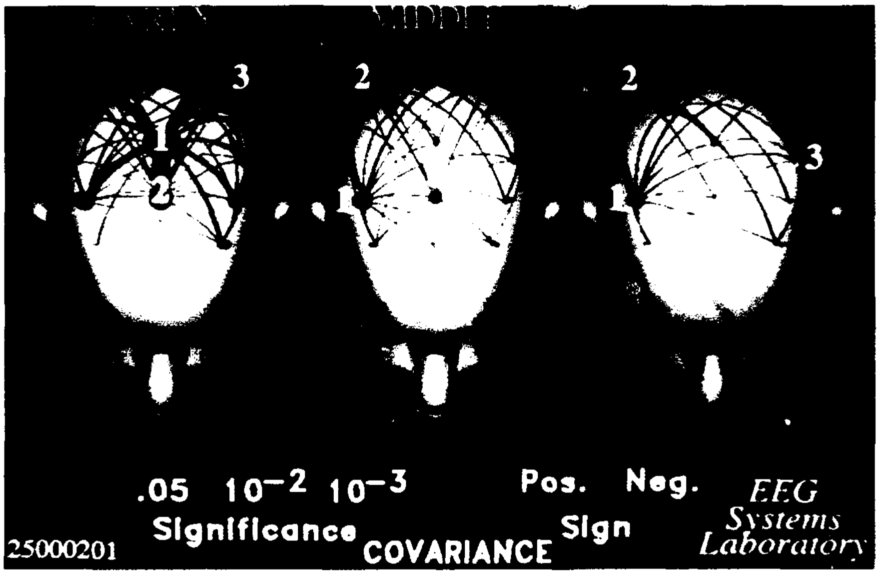


Figure 1. *Split-second neurocognitive patterns are affected by sustained mental work several hours before performance deteriorates. Each of the three heads shows an instant in time when five practiced USAF test pilot subjects held two numbers in working memory and awaited the next stimulus. The early period was during the first 6 of 10 to 14 hours of performance, the middle period was from hours 7 to 9 when performance was still accurate, and the late period was after 10 to 14 hours when task performance had deteriorated. A major shift in the pattern occurs from the early to the middle periods. Since dramatic changes in brain activity preceded deteriorated performance, such changes may be more sensitive indicators of the deleterious effects of sustained mental work than measures of overt behavior.*

Background

In one of many AFOSR-sponsored studies, neurocognitive patterns were measured as five USAF test pilots performed a battery of tasks, including a difficult working memory task, for up to 14 hours. (In the working memory task, subjects had to produce a precise isometric finger response with a force proportional to a random series of numbers. Subjects responded not to the current stimulus number, but to the number seen two trials earlier, requiring them to remember each number in the series for about 12 seconds). The patterns were dramatically affected by sustained mental work several hours before significantly deteriorated performance. Figure 1 shows the patterns during the instant of the memory task when the pilots were preparing to receive a new number while still remembering the last two numbers. Early, middle, and late periods of the recording sessions are shown. Striking changes occurred in the patterns after the pilots performed the task for 7 to 9 hours (middle), but before performance degraded. In particular, signal strength was reduced over midline motor rehearsal areas, and over the entire left hemisphere.

Payoff

Using a neural-network pattern classifier, it was possible to recognize the state of incipient performance impairment with an accuracy of over 80 percent. Replication and further development of the technology could lead to an early warning system to detect leading indicators of possible impaired performance due to fatigue or illness—a kind of pocket flight surgeon.

Contributing Organizations and People

Research is directed by Dr. Alan S. Gevins, EEG Systems Laboratory, San Francisco, and is supported by Dr. Alfred R. Fregly, program manager for cognition of the Directorate of Life and Environmental Sciences.

Light-Induced Gene Expression in the Circadian Pacemaker

Achievement

Dr. Michael Rea is conducting research into the biological basis of circadian rhythmicity at the Armstrong Laboratory, Brooks AFB, TX. Recent work from Dr. Rea's laboratory suggests that environmental light can synchronize circadian rhythms through the expression of specific genes within the circadian clock.

Background

Circadian rhythmicity in mammals is controlled by the action of a light-entrainable pacemaker located in a part of the brain called the basal hypothalamus, in association with two cell clusters known as the suprachiasmatic nuclei (SCN). The SCN receive sensory input when the eyes are stimulated by light. In the absence of temporal environmental cues, this pacemaker continues to measure time by an internal clock, driving biochemical, physiological, and behavioral rhythms that reflect the natural period of the pacemaker oscillation. This period usually differs [illegible] from 24 hours (i.e., circadian). When mammals are maintained under a 24-hour light-dark (LD) cycle, the circadian pacemaker becomes entrained such that the period of the pacemaker oscillation matches that of the LD cycle. In the entrained state, pacemaker-driven rhythms are phase-locked with the LD cycle. A sudden phase shift of the LD cycle, such as that which occurs during transmeridian jet travel, results in internal desynchronization of physiological rhythms leading to a temporary period of malaise and suboptimal performance, or jet lag. A similar condition may result when an imposed rest-activity cycle is incompatible with the LD cycle, such as occurs during shift work.

To investigate the effects of light on the circadian pacemaker, hamsters are maintained under conditions of constant darkness in cages equipped with running wheels. Without the entrainment effects of a 24-hour LD cycle, the hamster's activity level reflects the natural internal period of its pacemaker. This circadian activity rhythm is monitored as an indication of the status of the circadian pacemaker. These data are displayed as an actogram (figure 1), and the onset time of activity is used as a phase reference point for timing light exposures. In this way, the effects of single light pulses (30 lux for 15 minutes) administered at precise phases of the pacemaker oscillation can be studied.

When the animals are exposed to light pulses during the subjective day, no effect on the activity rhythm is observed (figure 1a). However, when light is given during the subjective night, a persistent alteration in the phase of the pacemaker (resetting) results. Light pulses given during the early subjective night cause phase advances (figure 1c) of the circadian activity rhythm.

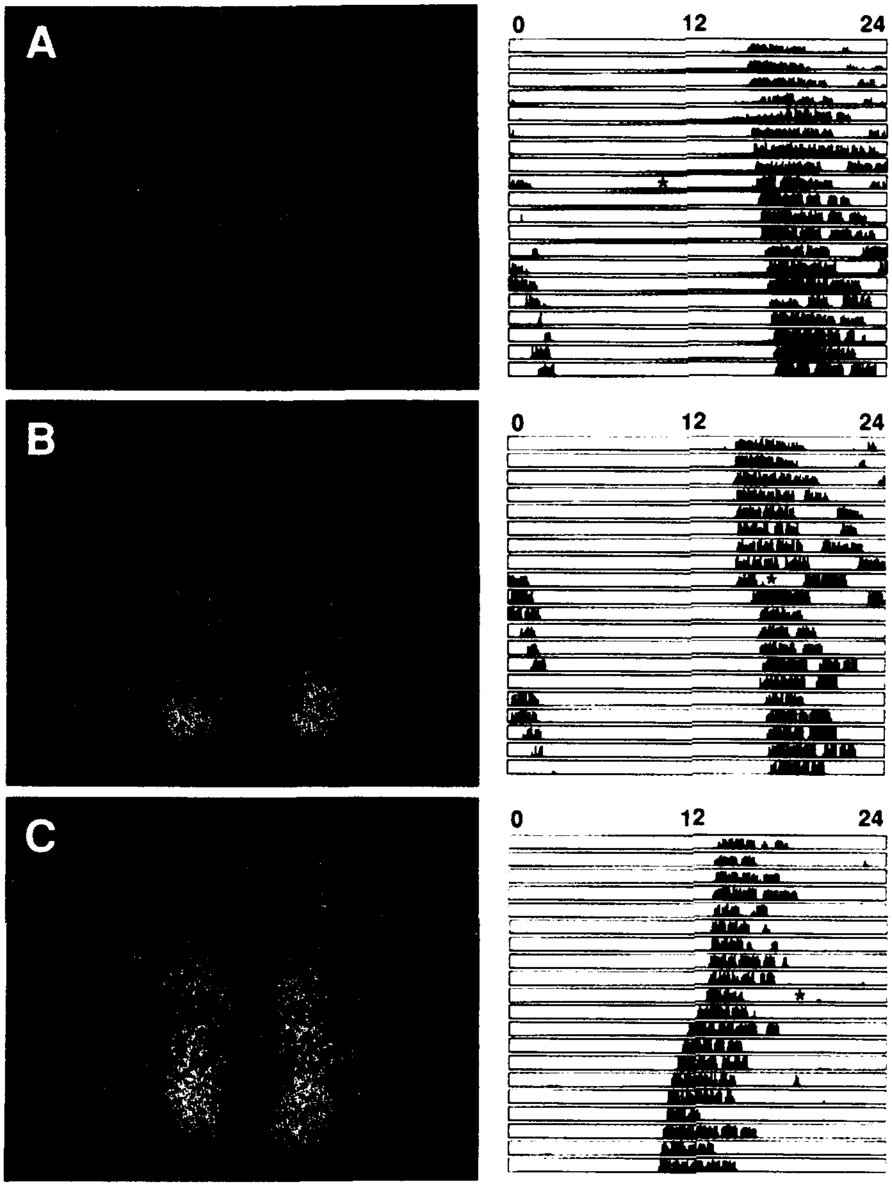
Payoff

The management of crew fatigue in both ground and airborne operations is a critical factor for maintaining mission success and safety. National defense and combat capability must be maintained 24 hours a day. Desynchronized circadian rhythms resulting from disrupted wake/sleep schedules, extended duty periods, and rapid transmeridian relocation are a prime cause of fatigue and human error in military operations. An understanding of the neurochemical mechanisms responsible for generating and entraining by light of circadian pacemaker oscillations would facilitate the development of pharmacological and/or environmental strategies for altering internal clock function. Ultimately, these strategies would alleviate the physiological and performance decrements associated with circadian desynchronization.

Dr. Rea found that light pulses that cause phase shifts of the circadian pacemaker also induce the expression of the c-fos transcription control gene among a distinct population of SCN cells. Only light pulses that cause phase shifts of the pacemaker induce c-fos expression in the SCN (compare figure 1a with 1b and 1c). This finding suggests that light-induced c-fos expression represents an early biochemical event in the response leading to alterations in circadian pacemaker activity. In addition, the pattern of c-fos immunoreactivity provides a map of SCN cells that are activated by the light pulse, perhaps identifying those cells that participate in the photic entrainment process. Finally, the pattern of c-fos expression is different in response to a phase-delaying versus a phase-advancing pulse (compare figures 1b and 1c), suggesting that different SCN cells may be responsible for phase delays and phase advances of the pacemaker. These results open a new frontier of research into the neurobiological basis of circadian rhythmicity.

Contributing Organizations and People

Dr. Michael Rea is a research biochemist and director of the circadian neurobiology research program at the Armstrong Laboratory. The project is managed by Dr. Genevieve Haddad of the Directorate of Life and Environmental Sciences.



Figures 1a, 1b, and 1c. *Effects of single light pulses on the phase of the circadian activity rhythm and the expression of the c-fos gene in the hamster SCN. Actograms are shown on the right. Horizontal lines represent activity records collected on successive days. Vertical bars represent wheel-turning activity occurring during 6-minute bins. Single 15-minute pulses of white light (30 lux) were administered at the times indicated (asterisks). Note that pulses given at mid-day (figure 1a) did not induce phase shifts, while pulses given during the early (figure 1b) and mid (figure 1c) subjective night caused phase delays or advances, respectively. False color images of sections of the hamster brain at the level of the SCN are shown on the left. These sections were immuno-stained for proteins produced by the fos gene family. Red and yellow denotes high- and moderate-density areas of immunoreactive cell nuclei. Note that gene expression in the SCN occurred in response to light exposure only during the subjective night, when light pulses reset the pacemaker.*

Microbial-Dependent Transformation of Toxic Metals

Achievement

An interesting bacterial strain is under investigation by Dr. Robert C. Blake, II, Department of Biochemistry, Meharry Medical College, Nashville, TN. These bacteria have shown an affinity for altering the chemical state of toxic heavy metals resulting in removal of the metal from solution.

A strain of the bacteria *Pseudomonas maltophilia*, found at a toxic waste site at Oak Ridge, has been studied in the transformation and precipitation of numerous toxic metals from solution. When the bacteria were added to a solution containing heavy metals, like mercury, chromium, selenium, lead, gold, silver, tellurium, or cadmium, the toxic metal was effectively removed within 1 to a few days (figure 1). In fact, with some of the metals, particularly gold, the glass flask containing the metal solution with the bacteria became coated with a thin layer of the metal (figure 2).

Background

Microorganisms can concentrate soluble metals in three basic ways. First, they can accumulate the metal either by adsorbing it onto their surface or by absorbing it through their cell wall. Since cell walls usually are negative in charge, positive metal particles may be attracted, like to a magnet. Some strains of bacteria make chemicals to coat their cell walls (like hair), which have a strong attraction for positive metal particles. Second, they can remove the soluble metal by a reaction with bacterially produced chemicals that react with the metals and cause them to precipitate from solution. This method may be useful in biomining. Third, they can transform the metal from one

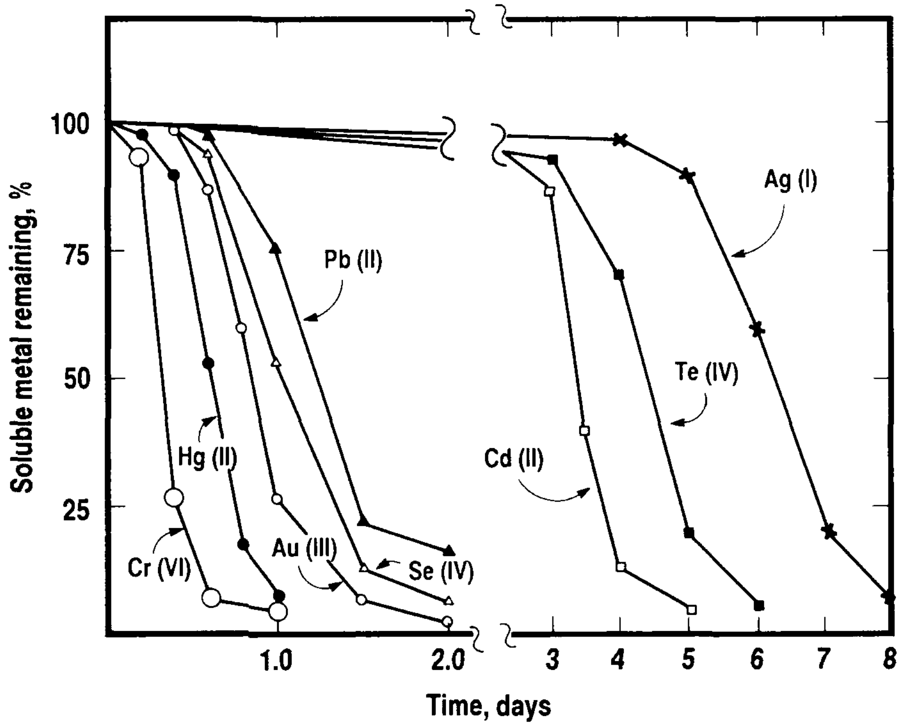


Figure 1. *Time course of the removal of soluble heavy metals from solution by bacterial bioreclamation.*

Figure 2. *Control and experimental flasks, showing gold plating out of solution onto the glass flask.*

chemical state to another to make it less toxic. The best example of that is a bacteria that absorbs the mercury in positive particle form then changes it, by using an enzyme, to the metallic elemental mercury (like the mercury in thermometers).

Removing toxic and heavy metal contaminants from liquid waste streams is one of the most important environmental issues facing the United States today. Although this issue has been addressed for many years, effective treatment options are limited. Chemical precipitation, filtering, and chemical extraction are the most commonly used procedures for removing heavy metals from water. However, these procedures have significant disadvantages, like incomplete removal, high energy and/or chemical requirements, and generation of toxic sludge or other waste products that require special disposal. These disadvantages are particularly apparent at the low metal concentrations often found in waste water.

Payoff

All microorganisms interact with metals. Two interactions that are of potential economic and industrial interest are the biosolubilization of metals from their ores (biomining) and the bioconcentration of metals from wastes or dilute mixtures (bioremediation/bioreclamation). Biomining permits extraction of metals from large quantities of low-grade ores. Bioremediation/ bioreclamation provides opportunities to remove metals that may be pollutants and to recover precious metals for recycling (e.g., silver from x-ray films).

The experiments done by Dr. Blake investigated whether the metal transforming properties of this organism possessed the performance characteristics necessary to permit exploitation of bacterial activities for bioremediation/bioreclamation. To be competitive with existing technologies metal-removing efficiencies must meet or exceed current rigorous performance standards. The *Pseudomonas* transformation of selenium, lead, silver, and mercury exceed that necessary to be competitive with existing technologies. It is evident that these bacteria are capable of the transformation and precipitation of high concentrations of soluble metals and could have biotechnology applications in waste water treatment and heavy metals recovery.

Contributing Organizations and People

This research is being conducted by Dr. Robert C. Blake, II, Department of Biochemistry, Meharry Medical College, Nashville, TN, and is supported by the Bioenvironmental Sciences Program managed by Lt. Col. T. Jan Cerveny of the Directorate of Life and Environmental Sciences.

Space Weather Prediction and Specification Capability Transitioned to Space Command, NORAD, and Air Weather Service

Achievement

Over the past several years, basic research programs have developed physical insight and models to specify and predict hazards to DOD assets operating in space. The complete analysis of the three types of data establishes magnetic merging as the dominant physical process controlling the energy transport at the magnetopause boundary. From this work we have shown that magnetic field-aligned currents in the dayside cusp region of the magnetosphere originate on field lines that are open to the solar wind. These currents carry considerable energy into the ionosphere, altering upper atmosphere dynamics and the drag on satellites. This investigation provides important new information on the coupling of energy from the solar wind into the magnetosphere, and the mechanisms that control the size and shape of the magnetosphere.

Background

One of the major problems in understanding and specifying the magnetosphere is ignorance of processes that control the size and shape of the magnetopause boundaries. It is the interaction of the solar wind with the magnetosphere at the outer boundary that determines energy transfer into near Earth space as well as the basic driving forces within the magnetosphere. Air Force and DOD satellites transit the magnetopause only during severe magnetic storms, and then only once a day. However, evidence from other sources is that the magnetosphere responds to disturbances on 10-minute time scales. Analytical and experimental studies were carried out to establish the basic characteristics of the boundary to elucidate the energy transfer processes and seek methods of specifying the magnetosphere boundary from low-altitude satellite measurements. This study by N.C. Maynard, W. Burke, and other colleagues of the Space Plasmas and Fields Branch of the Space Physics Division at Phillips Laboratory used a unique data set obtained from a spacecraft traversing the magnetopause simultaneously with measurements obtained from a low Earth polar orbiting satellite. Analysis of electrodynamic measurements (that is electric field, magnetic field, and particle data from the two satellites) showed unique features in the electric field data map from the magnetoshere down to the lower atmosphere. A unique signature of the electric field at the magnetopause identifies the location of the magnetopause at the altitude of polar orbiting satellites.

Payoff

These results are essential to the specification and prediction of space weather effects on space systems through the establishment of boundary conditions for operational magnetospheric specification and prediction models. These models (figure 1) are in the final transition process to the Military Air Command Air Weather Service, NORAD, and Space Command for specifications and alerts. The inclusion of time-dependent boundary conditions will greatly improve prediction of magnetospheric disturbances such as magnetospheric storms that degrade and destroy Air Force and DOD space systems.

Contributing Organizations and People

This research was conducted by Professors N.C. Maynard and W. Burke of the Space Plasmas and Fields Branch of the Space Physics Division at Phillips Laboratory. It is part of a program managed by Dr. Henry R. Radoski of the Directorate of Life and Environmental Sciences.

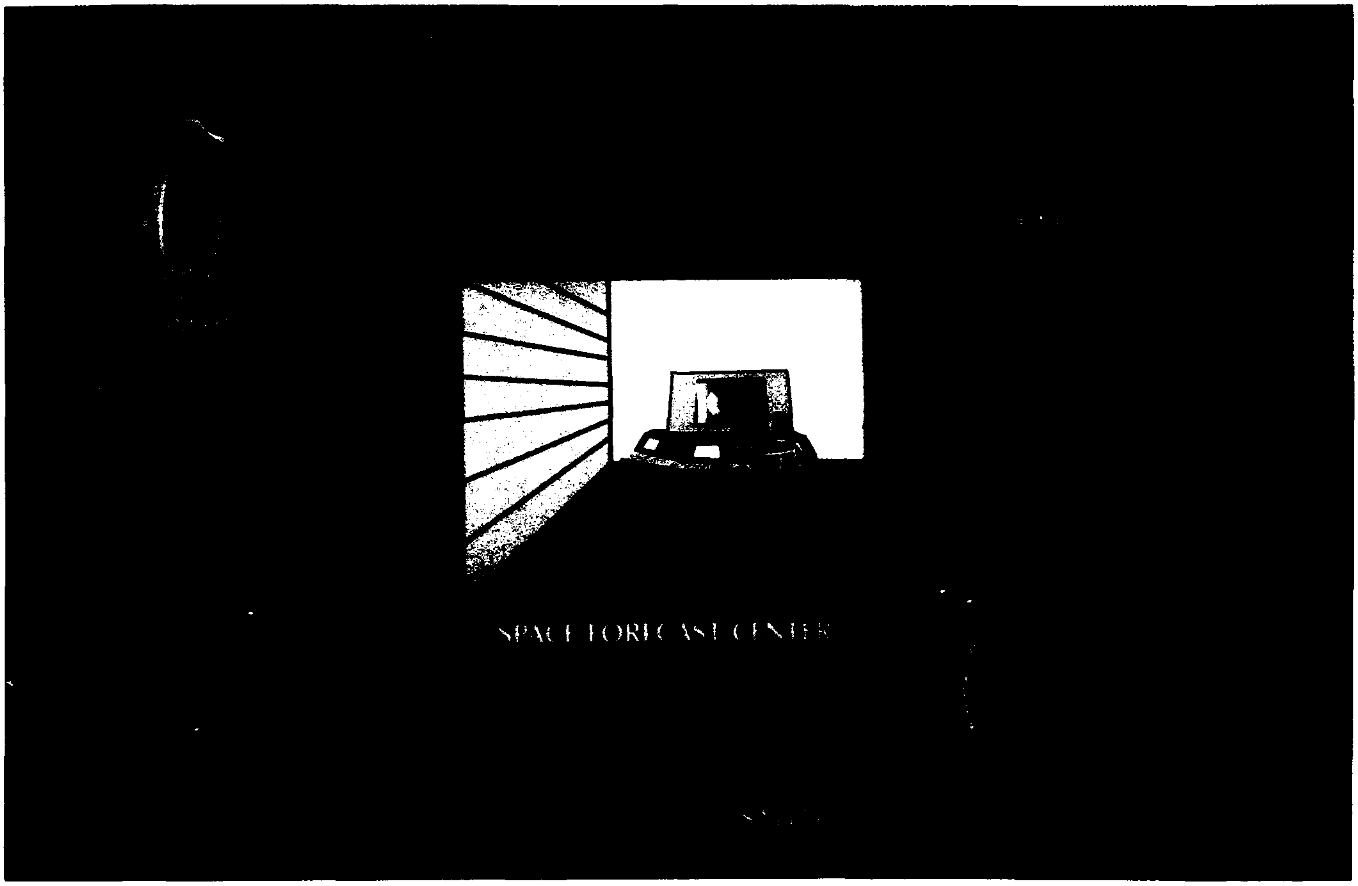


Figure 1. *Magnetospheric specification model.*

New Radar Technique Detects Charge Buildup in Clouds

Achievement

Dr. Paul Krehbiel and his colleagues at New Mexico Institute of Mining and Technology recently showed how polarization radar can detect charge buildup in clouds. This is a giant step toward protecting aircraft and spacecraft against triggered lightning. His technique may for the first time enable scientists to distinguish between electrically safe and dangerous clouds. This distinction is particularly important at the Kennedy Space Center where spacecraft can induce catastrophic lightning during launch, even when there is no natural lightning. It is also important for nonmetallic aircraft with low-voltage integrated circuits.

Background

The radar record in figure 1 shows 2 minutes of the cross-polar return during this storm. The cross-polar return is obtained by transmitting a horizontally polarized signal and measuring its vertically polarized return. Notice the sawtooth pattern in the radar record. The sharp vertical lines in the sawtooth correspond to lightning discharges (verified by other data). Before each of these discharges the signal ramps upward. These ramps appear to be the result of ice crystals becoming aligned in response to the charge built up before each lightning discharge.

Now that Dr. Krehbiel has shown he can detect crystal alignment with a polarized radar, he plans to test other polarization schemes to find the most reliable technique. His next step will be to test circular polarization. He also plans to deploy his radar to the Kennedy Space Center during the summer of 1991 as part of a large field program involving numerous other radars and aircraft.

Payoff

Dr. Krehbiel performed his experiment on a New Mexico thunderstorm during the summer of 1989. He used a 3-cm wavelength polarization radar to look at the upper regions of the cloud. He kept the radar pointed at the same volume element throughout the experiment (figure 1). By comparing various combinations of polarized signals, he was able to detect what appears to be increased ice crystal alignment just before each lightning strike.

Contributing Organizations and People

Dr. Krehbiel performed this research as part of a program managed by Lt. Col. James G. Stobie of the Directorate of Life and Environmental Sciences.

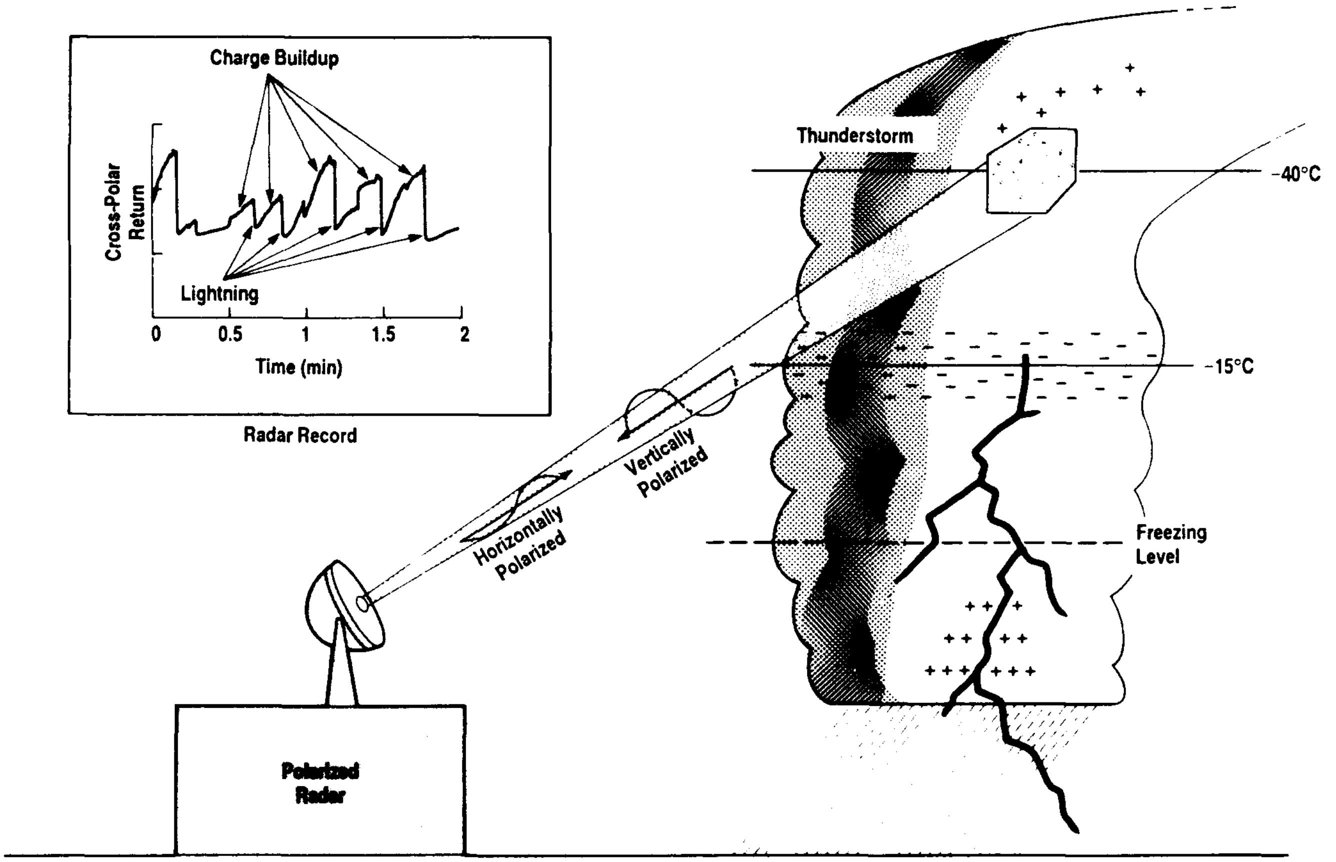


Figure 1. *This diagram shows how the radar antenna remained fixed on a specific volume element in the storm. This volume was at approximately 33,000-ft. altitude where the temperature was -40 °C. At this temperature many of the ice crystals will likely be in the shape of hexagonal columns. The cross-polar radar record shows an apparent increase in alignment of these crystal columns in response to local charge buildup before each lightning strike.*

DIRECTORATE OF MATHEMATICAL AND COMPUTER SCIENCES

The mathematical sciences research of the Directorate of Mathematical and Computer Sciences focuses on the modeling, analysis, and control of complex systems and phenomena. Computer sciences research emphasizes increasing the capability to exploit high-performance computing for both embedded applications and engineering design.

This year's highlights illustrate a wide range of scientific activity. Three accomplishments deal with our investigation of the properties of the emerging paradigms of neural networks and wavelets for solving critical Air Force problems in detection and classification, as well as other aspects of signal processing. Recent experience in Operation Desert Storm has shown the importance of collecting, processing, storing, and interpreting sensor data. These accomplishments are geared toward meeting the requirements imposed by future threats.

The directorate's research program in control is the leading national research program in the field. Two highlights reflect part of the scope of this program. One illustrates our commitment to pursuing nonlinear control methodologies for the development of advanced agile aircraft. Another illustrates a significant algorithmic advance in our ability to incorporate realistic measures of system complexity, such as in hypersonic air-breathing engines, into control system design.

Last year we highlighted progress in developing new algorithmic techniques for solving large linear programming problems (involving hundreds of thousands or millions of variables). Ideas from our supported research on interior methods for these problems have been incorporated into a computer program production code OB1, which is now being used by the Mobility Command to analyze many of its route scheduling and transportation problems.

These highlights constitute a small portion of our research accomplishments. We are undertaking many new research directions to pave the way for future Air Force transitions. Contact the appropriate program manager (listed in the directory) for details of ongoing work.

Linear Programming

Achievement

AFOSR has supported the development of an advanced optimization technology that has significantly increased the Air Force's ability to solve large, complex models. In addition to improved algorithms, AFOSR has supported applications of these algorithms to novel model formulations to provide new capabilities in a number of areas. Professor Olvi Mangassarian of the University of Wisconsin has used a single model to provide improved methods of classification and a new and potentially superior algorithm to train neural networks.

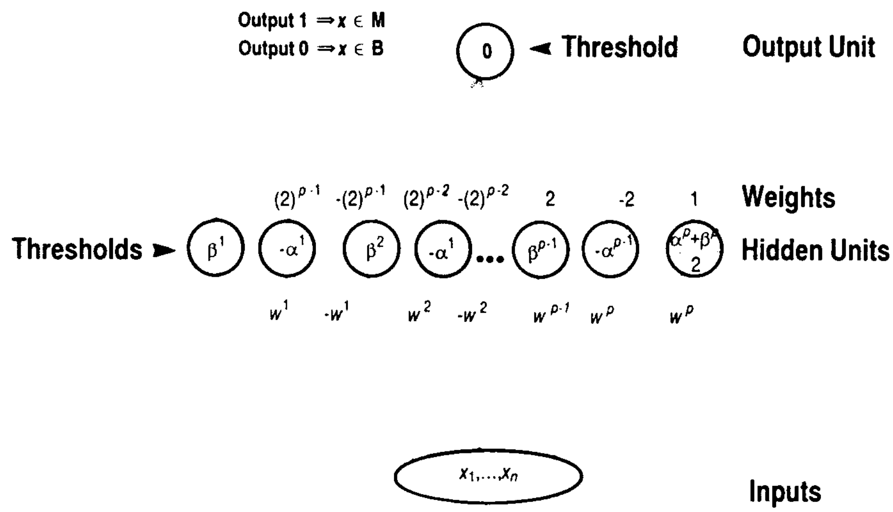


Figure 1. *Each input ($x_1, \ldots, x_n$) yields an output in either set M or set B. The linear program determines the structure of the neural net needed to separate the input on the basis of the output. It determines the number of hidden units needed, the weights, ($w^1, \ldots, w^p$), and the thresholds.*

Background

A result known since 1965 is basic to this new technique. The result is that a single linear program (LP), solvable in polynomial time, can be used to determine a plane that separates two disjoint convex objects. When these objects are the convex hulls of two sets of points to be classified, the same linear program generates a linear form whose value determines the set into which a given point falls.

Payoff

When the convex hulls do intersect, a sequence of linear programs is necessary to perform the separation, but the sequence is no longer than the dimensionality of the sets of points. This technique has been successfully applied in classifying malignant and non-malignant cells from breast tumors, and in this form is being used at the University of Wisconsin hospital as a very accurate diagnostic aid. The same technique could be used to provide accurate recruit evaluation or pilot selection tools.

The same classification scheme can be thought of as a trained feed-forward neural network. The training of this neural net can be done more efficiently by the linear programming approach discussed above rather than by back propagation, as is customary. In addition, the LP approach always achieves 100 percent correctness on the training set, has a comparable correctness rate on new data, and automatically determines the number of hidden units required by the neural net (figure 1).

Contributing Organizations and People

This research was performed by Professor Olvi Mangassarian of the University of Wisconsin. The program manager is Dr. Neal Glassman of the Directorate of Mathematical and Computer Sciences.

Large-Scale Computing in Control Law Design

Achievement

Recent research by Professor Alan J. Laub and his group at the University of California—Santa Barbara, is paving the way for effective large-scale computing in control and filtering. A new class of algorithms, based on the so-called matrix sign function, has proved particularly effective in solving the algebraic Riccati equation. These exciting new results are part of an overall program devoted to developing algorithms capable of handling system models with hundreds or even thousands of states. Most of Professor Laub's research is directed specifically toward the solution of certain critical "bread-and-butter" matrix equations that arise in control law design. Riccati equations, together with their linear counterparts known as Lyapunov equations, are the most common types and their role in control and filtering is rather analogous to the role Navier-Stokes equations play in computational fluid dynamics. The new classes of algorithms being studied are especially well suited to parallelization and vectorization and have been used successfully to solve fairly large-order (several hundred) problems on Cray supercomputers. Early experiments on a Cray Y-MP with four processors are very encouraging. A 100th-order Riccati equation, for example, can be solved in 0.8 seconds and a 200th-order equation in just over 3 seconds.

Background

Professor Laub has worked on numerically reliable and stable algorithms for control law design for over 15 years. Much of his work has been embedded in

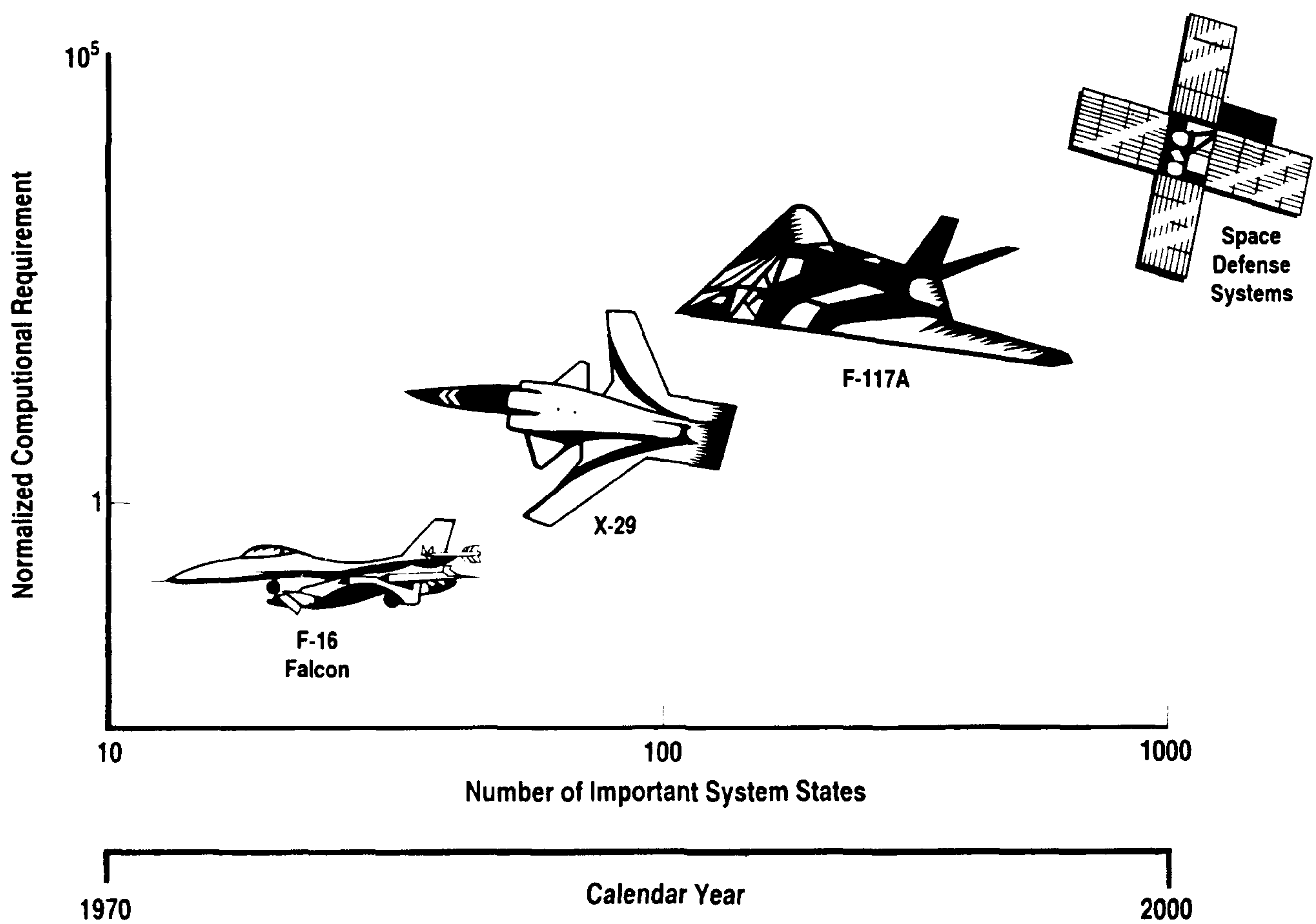


Figure 1. *Growth in computational requirements.*

current computer-aided control system design software used both by Air Force Laboratories and Air Force contractors. Such software includes both packages developed in-house as well as software available commercially (such as Ctrl-C, Easy5, Matlab, and Matrix-X). However, such software will be inadequate for many future systems of critical interest to the Air Force. Figure 1 illustrates in a stylized way the growth in computational requirements fo: some typical Air Force programs.

Payoff

Many modern control law design methodologies give rise to high-order numerical problems whose solution will depend crucially on Professor Laub's AFOSR-sponsored research. For example, finite element models of large space structures can easily have hundreds of states. Control systems for hypersonic aircraft provide even more compelling motivation for research in large-scale computing. Hypersonic engines alone will have hundreds or perhaps thousands of actuators and sensors. Moreover, unprecedented coupling of engine, airframe, and control systems in which almost all variables of flight control, engine performance and stability, and thermal management are interrelated in real-time yield computational challenges of astonishing magnitude. For example, most realistic measures of control system complexity and difficulty in hypersonic airbreathing engines typically range up to 10 times that for the space shuttle main engine. Control law design for such systems will place a severe or intolerable computational burden on existing algorithms and software. Indeed, many of the numerical problems that must be solved for modern control design are all but impossible with existing methods.

Contributing Organizations and People

This AFOSR-sponsored research, managed by Dr. Marc Jacobs for the Directorate of Mathematical and Computer Sciences as part of the program in dynamics and control, is laying the foundation for the next generation of computer-aided control engineering software. As Cray-type computing becomes available in desk-top workstations, tomorrow's Air Force control system designers will be routinely using the software and algorithms being developed today.

Advances in Nonlinear Feedback Control

Achievement

Professors C.I. Byrnes and A. Isidori at Washington University in St. Louis, MO, have developed new methods to shape the response of complicated nonlinear systems using feedback strategies that can be systematically designed by a novel synthesis of methods drawn from geometry and nonlinear dynamics. The problems of stabilizing and controlling nonlinear systems are limiting factors in the design of many DoD systems. Such systems include those investigated in current research and development efforts in the aerospace industry devoted to the active control and stabilization of high-performance aircraft operating in nonlinear flight conditions involving agility and high angles of attack.

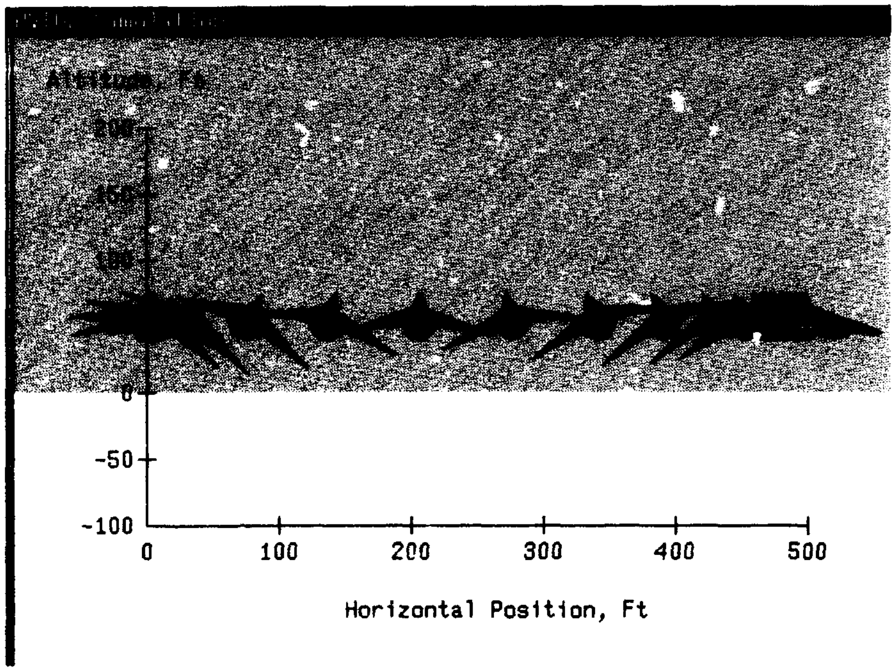


Figure 1. *Prototype vertical take-off and landing aircraft simulation.*

Background

Because linear systems exhibit much more predictable and well-understood behavior, the control of linear systems has been more highly developed than the control of nonlinear systems. For this reason, current approaches to flight control in the presence of nonlinear effects, e.g., "gain scheduling," have typically involved finding an "equivalent" linear system, for which a controller is then designed using existing linear methods. However, for the highly nonlinear maneuvers performed by advanced nontraditional aircraft (figures 1 and 2), involving increased agility and higher angles of attack, the limitations of conventional design methods stem from the lack of a reasonable "equivalent" linear system that incorporates in some way the increasingly dominant nonlinear effects. The recent advances made by Professors Byrnes and

Figure 2. *F-15 STOL Demonstrator.*

Isidori offer a methodology to overcome some of these limitations.

Underlying the success of linear systems design is the superposition principle, which makes possible analysis of the steady-state system response to a complex input signal in terms of the response to simple input signals. This is basic to both the frequency domain approach, which is popular for its intuitive graphical criteria, and the state space approach, applying powerful variational methods to a state space model of the system and employing differential equations to describe the system evolution. The approach pioneered by Professors Byrnes and Isidori incorporates geometric methods in control and in the theory of dynamical systems to provide an analysis of the steady response of nonlinear control systems. The main techniques for this analysis were discovered in the course of a 5-year research effort that produced systematic design methods for feedback stabilization of broad classes of nonlinear systems, recently settling a long-standing problem concerning feedback stabilization of a rigid body model for a rigid spacecraft controlled by pairs of gas jets.

Payoff

The most significant application of this geometric approach to analyzing steady-state response of nonlinear systems is the recent solution of the nonlinear regulator problem, one of the major problems in control system design. This is the problem of designing a feedback compensator that will ensure that the system to be controlled asymptotically tracks a desired reference signal (or trajectory), while at the same time rejects an unwanted disturbance signal that, if unattenuated, would severely compromise system performance. The methods underlying this unanticipated breakthrough incorporate nonlinear enhancements of basic frequency domain tools, such as the concept of transmission zeros, into a geometric approach to nonlinear state space analysis. This approach leads to conditions for solving the nonlinear regulator problem that retain the intuitive content of classical linear frequency domain methods. More importantly, an essential component of this advance is the actual form of the feedback compensation scheme, which is computationally tractable. In close analogy with the linear variational methods, the structure of the feedback law is that of a nonlinear proportional error compensator where the nonlinear feedback "gains" can be computed "off-line" by solving a nonlinear partial differential equation, quite similar to very important roles played by the Riccati equation in linear system design. These advances point both to a powerful new tool for the systematic design of nonlinear feedback systems and to a new approach to computational nonlinear control in high-performance aircraft. Figure 1 is a simulation of a planar VTOL aircraft being controlled by such a nonlinear regulator during a horizontal hovering maneuver, with a desired transfer of 500 feet. By incorporating the nonlinear coupling between wind axis moments and rectilinear accelerations into both the PVTOL model and the controller design, the closed-loop system achieved horizontal transfers of 10,000 feet with negligible vertical drop. This is in sharp contrast to a standard linear controller for which transfer was limited to fewer than 11 feet. Similar nonlinear couplings arise between the propulsion forces/moments and the aerodynamic forces/moments of advanced Air Force aircraft such as the F-15 STOL Demonstrator (figure 2). At high angles of attack, the F-15 STOL aircraft's propulsive thrust vectors push its performance envelope beyond conventional aerodynamic limits. The development of a systematic design methodology for nonlinear systems, and its application to highly nonlinear aerospace guidance and control problems, is the goal of the research being performed by Professors Byrnes and Isidori.

Contributing Organizations and People

The Directorate of Mathematical and Computer Sciences has long recognized the potential importance of innovative research in the field of nonlinear dynamics and control, and has been a leader in supporting basic research in this area. This is now a widely held view. In 1989, Professor Byrnes was honored as a Fellow of the IEEE "for contributions to feedback stabilization and the control of linear and nonlinear systems." Professors Byrnes and Isidori are performing their research under a grant managed by Dr. Marc Jacobs for the Directorate of Mathematical and Computer Sciences.

Multiresolution Signal Analysis and Data Fusion

Achievement

Professor Alan S. Willsky and his colleagues at the Massachusetts Institute of Technology have recently developed a new mathematical framework for the integrated processing and statistical analysis of complex signals and data sets obtained from heterogeneous suites of sensors. This framework combines in a novel manner the emerging theory of wavelet transforms for multiresolution signal representation and the well-established systems and control techniques of optimal estimation and Kalman filtering. The framework provides a flexible methodology for designing extremely efficient and highly parallelizable algorithms for a broad range of problems including sensor fusion, event or anomaly detection, and pattern matching and recognition.

The collection, processing, storage, and interpretation of sensor data are critical and often performance-limiting components of most, if not all, Air Force systems at levels encompassing tactical, strategic, and intelligence missions. Indeed, developing targets of dramatically reduced observability demands systems that sense and extract every bit of discriminating information across a much larger portion of the electromagnetic and/or acoustic spectrum than has heretofore been required. Also, for a variety of reasons the requirements on remote sensing systems, e.g., to assess tactical military threats, as in the Persian Gulf, or to identify and locate strategically relocatable targets, have increased substantially. Furthermore, these changing and developing threats have motivated a variety of advanced sensor systems under programs ranging from the Atmospheric Defense Initiative to the Advanced Warning System to upgrades of platforms such as DSP and AWACS, providing sensors that offer the promise of increased coverage, sensitivity, resolution, and spectral diversity. Finally, the continuing enhancement of operational computing systems makes possible, and in fact demands the consideration of, signal and image processing functions that could not have been proposed realistically even 10 years ago.

Background

While previous work had indeed indicated the promise of multiresolution signal processing methods, the work on such methods had proceeded without a firmly grounded analytical framework that could provide the basis for a rational and broadly applicable design methodology. The emerging theory of wavelet transforms, however, gave life to the idea that such a methodology might be achievable. What Professor Willsky and his colleagues have done is to take a major step toward reaching this goal by providing a statistical modeling and filtering framework complementary to the wavelet transform in much the same way that the framework of stationary stochastic processes and lumped dynamic models complement the Fourier transform. The result is a new theory of multiscale statistical modeling that is not only rich enough to capture a broad range of physically meaningful phenomena (including signals with fractal characteristics as well as those traditionally modeled using rational spectral methods), but also powerful enough to lead to corresponding theories of statistically optimal signal processing that should prove to be as valuable as their more traditional counterparts.

The key to this approach is the observation that the wavelet transform provides a *dynamic* representation of a signal or a phenomenon, but in this case the dynamics are not in time, but rather in *scale.* This leads naturally to a pyramidal description of signals at multiple resolutions, allowing one to capture any multiscale features in the phenomenon under study and to model multiresolution measurements as observations at corresponding levels in the pyramid. Furthermore, Willsky's work shows that such a modeling framework leads naturally to several computationally attractive and highly parallelizable algorithmic structures for optimal multisensor signal processing. Indeed, thanks both to the use of coarse solutions to guide fine-scale processing and to the fact that wavelet transform computations can be performed extremely quickly, multiscale counterparts of optimal Wiener and Kalman filtering are actually far *more* efficient (in terms of operations per data point) than their single-scale, traditional counterparts. These new algorithms can accommodate, without *any* increase in algorithmic complexity, multisensor data fusion problems to which standard methods are completely inapplicable. For example, as illustrated in figure 1, it is straightforward in this setting to design an algorithm that uses coarse-resolution data to optimally guide the interpolation of fine-scale, but relatively sparse measurements or, as shown in figure 2, to assess the performance of such a sensor architecture as a function of coarse sensor resolution. Also, while these figures illustrate the application of this methodology to

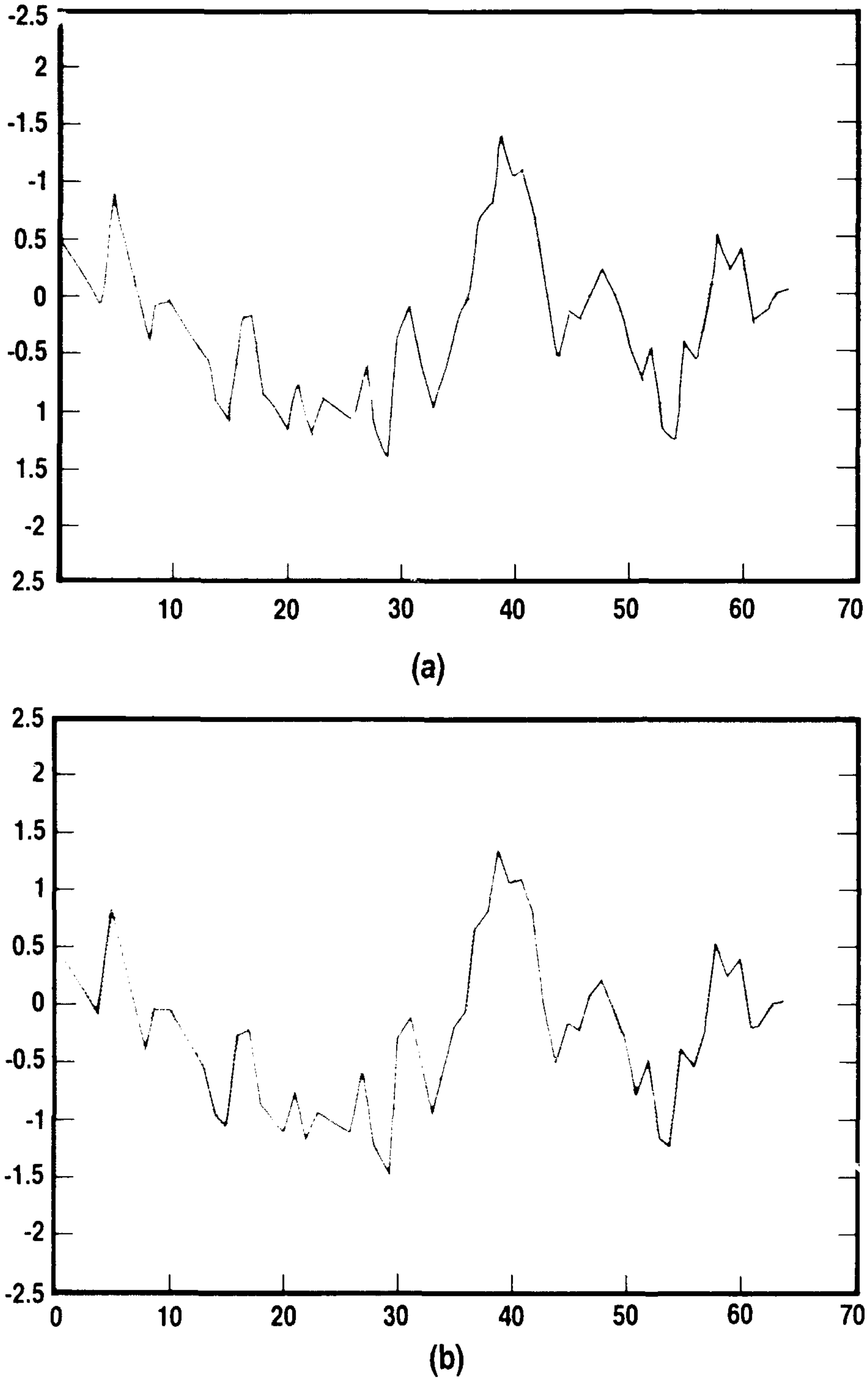


Figure 1. *(a) An illustration of a signal (solid) and a set of noisy, fine-scale measurements available only at the ends of the interval and their optimal, unaided smoothing and interpolation (dashed). (b) The optimal smoothing and interpolation when the data in (a) are fused with coarser resolution mea-surements over the full interval.*

one-dimensional data, the techniques apply equally well to imagery.

While many aspects of this methodology are still under development, applications to several problems of direct relevance to the Air Force have recently been initiated. In particular, Professor Willsky and his colleagues are using these techniques to develop multiresolution algorithms for optimal matching of multiple data sets. The results of this investigation will be algorithms directly applicable to problems of data registration, terrain map matching, and stereo imaging. Also, Willsky is involved in developing multiresolution algorithms for signal and image segmentation and texture identification. Of particular interest in this investigation is the localization of anomalous objects or image regions. Such methods should be applicable to the detection of manmade objects (such as strategically relocatable targets) in an otherwise natural scene. The most significant application, however, is in the area of multisensor fusion. In particular, one postulated benefit of multisensor fusion is superior clutter suppression based on the exploitation of the correlation in clutter response across space, time, and sensor.

Payoff

Present and future military missions present substantial challenges to the engineering and mathematics community and require the development of new and innovative formalisms that offer the possibility of revolutionary rather than evolutionary improvement. Multiresolution processing is one such framework that appears to be particularly well-suited to a variety of Air Force problems. Such a framework offers the possibility not only of producing superior methods for fusing multispectral and multiresolution sensor data (e.g., from spatially distributed IR and ESM sensors, various band radars, etc.) or of accurately and efficiently representing features that have a fractal or multiresolution character (such as the terrain variations and patterns used in cruise missile terrain guidance systems). It also offers the possibility of developing algorithms that overcome the often daunting computational demands of multisensor data processing problems by solving coarse (and therefore computationally simpler) versions and using these to guide

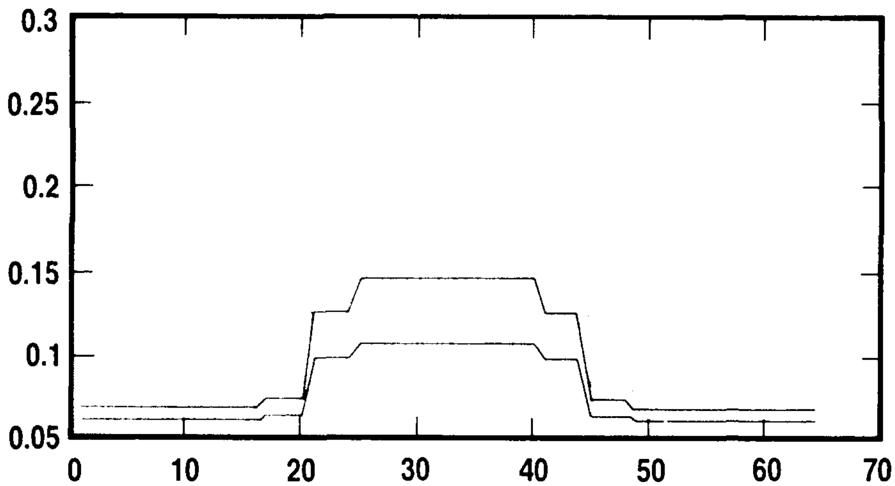


Figure 2. *An illustration of the smoothing and interpolation error variances for the fusion problem in (1a). Here the several curves correspond to situations in which the fine level data are fused with a second data set with different resolutions. The top curve corresponds to performance if no such second data set is available, while the other curves show the achievable improvement as data of increasingly fine resolution are fused.*

(and thus speed up) their higher resolution counterparts.

The use of Willsky's multiresolution signal processing methodology to realize the benefits of multisensor fusion is under development through the Advanced Concepts and Analysis Branch of the Surveillance Technology Division of the Air Force's Rome Laboratory.

Contributing Organizations and People

Professor Willsky's research has been sponsored for several years by the Directorate of Mathematical and Computer Sciences. This project is currently managed by Dr. Marc Jacobs.

Aerial and Space-Based Reconnaissance Imaging

Achievement

Cognitech, Inc., is developing new procedures toward a system that can reconstitute a severely blurred image, or a remote-sensing photograph that has been degraded by signal noise. Typical blurring distortions arise from unevenly heated atmospheric layers. When an image is transmitted over RF, channel noise can result in an image with "snow," as is familiar from a video monitor. Meeting the challenge of image reconstruction required significant mathematical advances, which surprisingly came out of the study of shock waves in fluid (gas) dynamics. The idea is that a shock wave produced by a nonlinear effect in a gas is a valid model for a sharp edge (discontinuity in intensity) in a visual image.

Background

The essential technical innovation is the construction of a high-order Essentially Nonoscillatory (ENO) shock-capturing algorithm (similar to those used in analyzing gas dynamics). If u_0 (x, 0) is the original blurred "image" (here, it is one-dimensional), then the backwards heat equation, which is inverse to the Gaussian blurring process, can be applied with an ENO step. This results in effective suppression of spurious oscillations while enhancing edges and fine-scale details.

A thorough mathematical analysis of the resulting algorithm shows that it is theoretically sound for problems whose parameters come from practical situations. Direct implementation of the procedure has had gratifying success. In fact, sometimes superresolution can result from applying the method. That is, features reappear (in the reconstituted image) that were not seen in the unblurred original, but were present in the actual scene!

The physical theory of conservation laws leads to a number of robust finite-difference methods and other numerical solution methods. It is remarkable that this conservation law approach figures strongly in both deblurring and denoising procedures. For noise removal, it has proved to be highly effective to replace the data at each time step with an ENO approximation, followed by "shaking" the intensity surface back and forth in time. Further improvements in this approach are expected by using known statistics of the noise.

The left half of figure 1 shows a blurred image of a fighter plane consisting

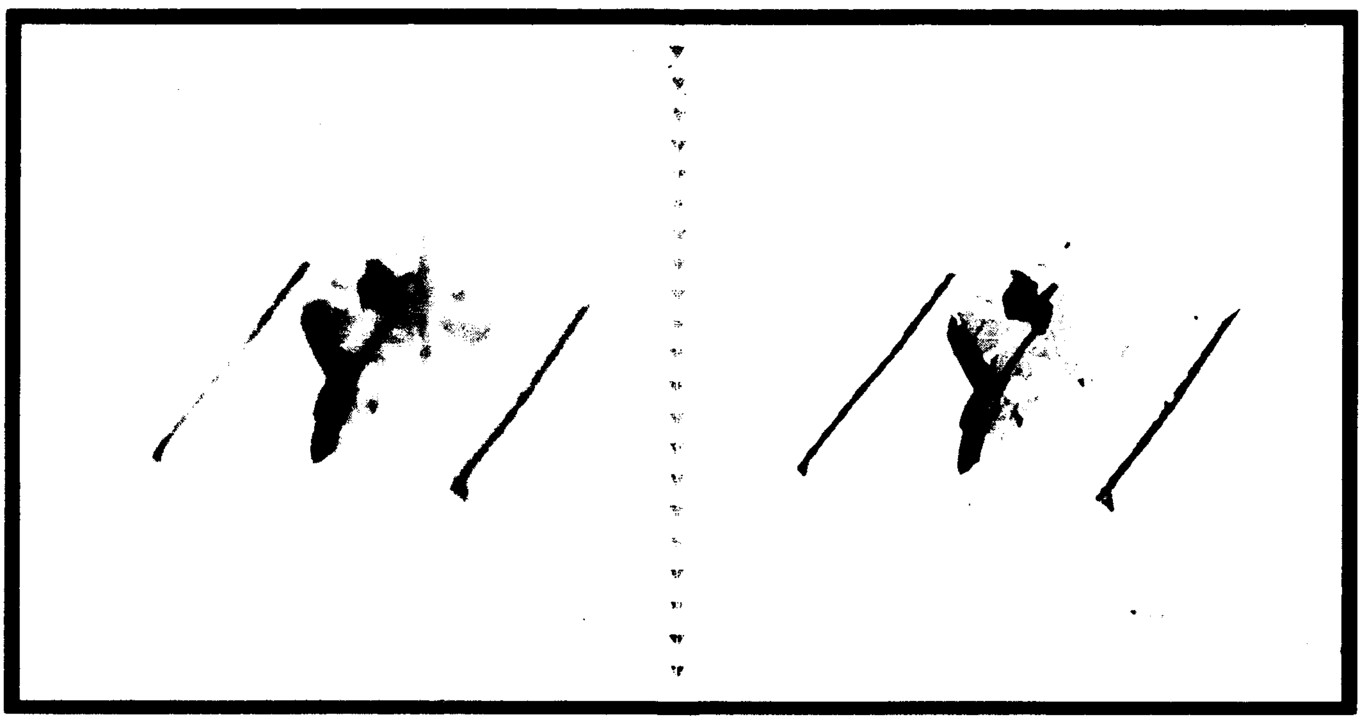


Figure 1. *Image enhancement by advanced numerical inversion techniques.*

of 256 x 256 pixels with 256 gray levels. The blurring was caused by convolution with a Gaussian kernel with a 50-pixel area (60 iterations with a heat operation having $\Delta t = .1(\Delta X)^2$.

The right half of the figure shows the resolved reconstruction resulting from applying ENO shock-capturing.

Payoff

With increased Air Force reliance on aerial and space-based reconnaissance imaging, these advances could significantly improve Air Force image analysis and infrared spectra capability. Classical enhancement techniques using linear and/or statistical methods have tended to produce spurious oscillations (ringing) and excessive smearing of edges. The Cognitech nonlinear approach greatly suppresses these undesirable effects.

Contributing Organizations and People

Current efforts now focus on combining deblurring and denoising into one package. Cognitech research personnel involved in last year's effort were Dr. Stanley Osher and Dr. Leonid Rudin, the principal investigators on the project. The work was managed by Dr. Jon Sjogren of the Directorate of Mathematical and Computer Sciences.

New Language and System for Developing Highly Reliable Avionics Systems in Ada

Achievement

In a recent 4-year program, AFOSR has sponsored design and development of a new language, Task Sequencing Language (TSL), for specifying distributed and concurrent Ada software. TSL is a language for defining new kinds of system concepts, such as patterns of communications (e.g., repeating sequences of similar events are a common example of a pattern) that are crucial in specifying distributed software. TSL constructs are not contained in Ada or any other programming language. By using TSL, specifications of synchronization, data communication, and timing properties of Ada systems can be written in a precise, machine-processible language. Such specifications in TSL are called "formal specifications." They can be automatically compiled and used to monitor the actual software for errors (i.e., violations of the specifications) at runtime. Experimental runtime monitoring tools for TSL have also been developed.

Background

Current state-of-the-art aircraft/avionics computing systems are distributed, time-sensitive, software systems running on multiple computers. "Distributed" means that various functions are performed on different computers, often requiring a high degree of simultaneous computation; "time-sensitive" means that

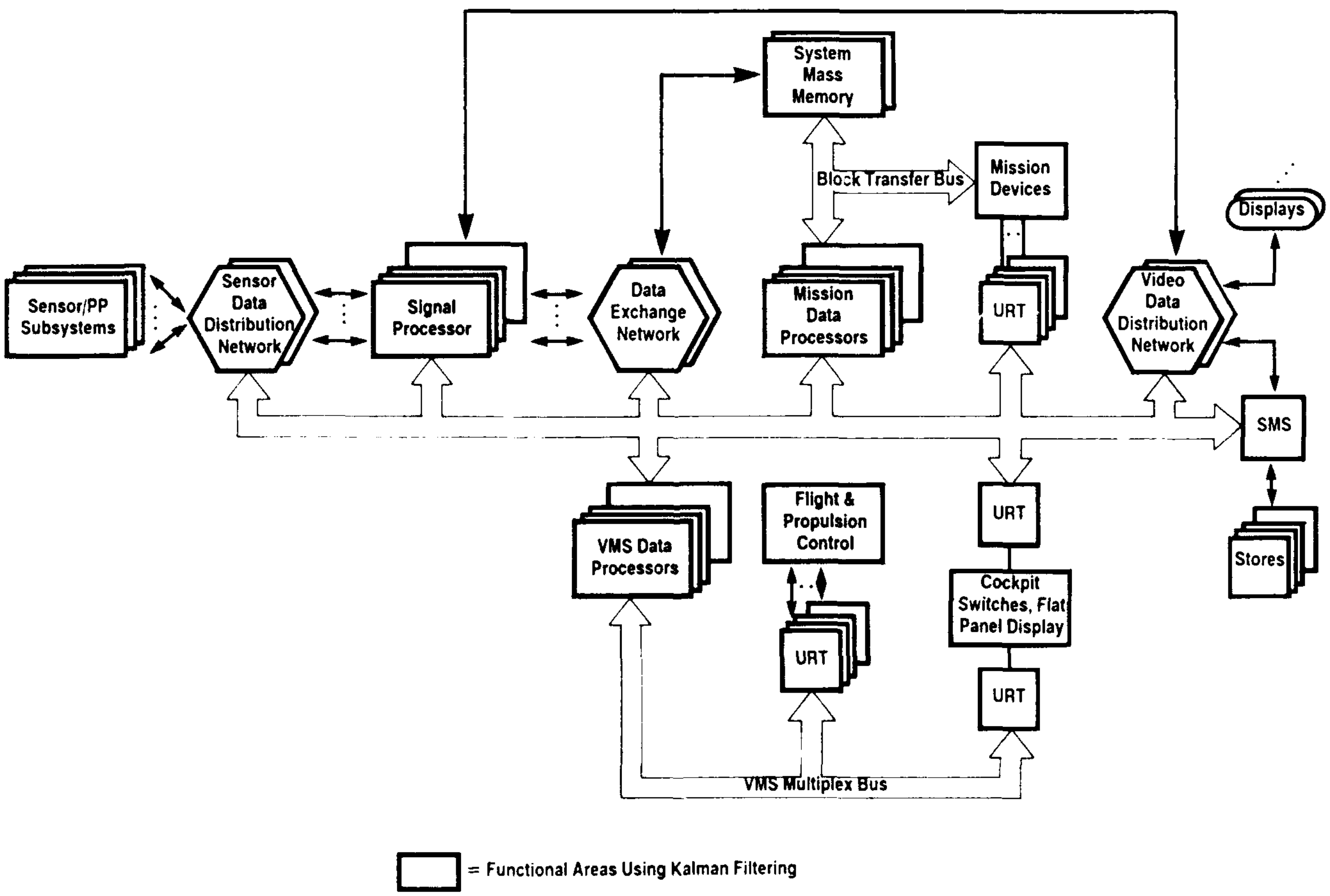


Figure 1. *ATF generic avionics architecture.*

system functions must be performed within various time bounds for an overall system to operate correctly. Examples of these systems vary widely, from onboard avionics controlling the various functions of a single aircraft (figure 1) to systems that provide logistics and integrated planning for large numbers of aircraft.

The use of distributed computing in avionics will continue to increase dramatically due to a variety of factors, including increasing sophistication of guidance, weapons, and logistics subsystems, development of autonomous (robot) aircraft, and requirements to optimize deployment on a worldwide scale (figure 2).

Production and maintenance costs and reliability issues with such systems are compounded by the fact that the kinds of computers involved and the basis by which they exchange information vary widely (e.g., computer networks may include satellite links), and different parts of the software may be written in different programming languages. Various studies have shown that the software has become the most critical factor influencing costs and reliability.

In the past few years, the DOD Ada language has seen increasing use in the area of command and control systems software, including distributed systems and avionics, to reduce costs and duplication of effort by using a single standard language. The Ada*9X* effort is now underway to revise Ada for use in the 1990's in the light of recent experiences with these kinds of applications. This includes plans to extend the Ada language by adding some of the new language features that have been designed and researched under both Defense Advanced Research Projects Agency (DARPA) and AFOSR sponsorship. These new features make it possible to use new design and testing techniques to improve the reliability of Ada software, as explained next.

In standard practice, "requirements specifications" for software are written informally in English. They are supposed to define the properties and required functionality of a system. But they are usually ambigious and incomplete, leading to misunderstandings and expensive errors during software development that often do not get corrected until delivery and field testing. This is particularly true in distributed, time-sensitive systems that involve synchronization, timing, and interprocess communication that are not normally needed in sequential (single process) software.

TSL is designed as an extension of Ada and its runtime monitoring tools can be used in conjunction with any standard Ada compiler. TSL allows a new generation of techniques to be applied to the process of building distributed/concurrent Ada software. Precise formal specifications can be written before developing the software, and compared with the system requirements to uncover ambiguities. The formal specifications are then used to guide development of the software, and

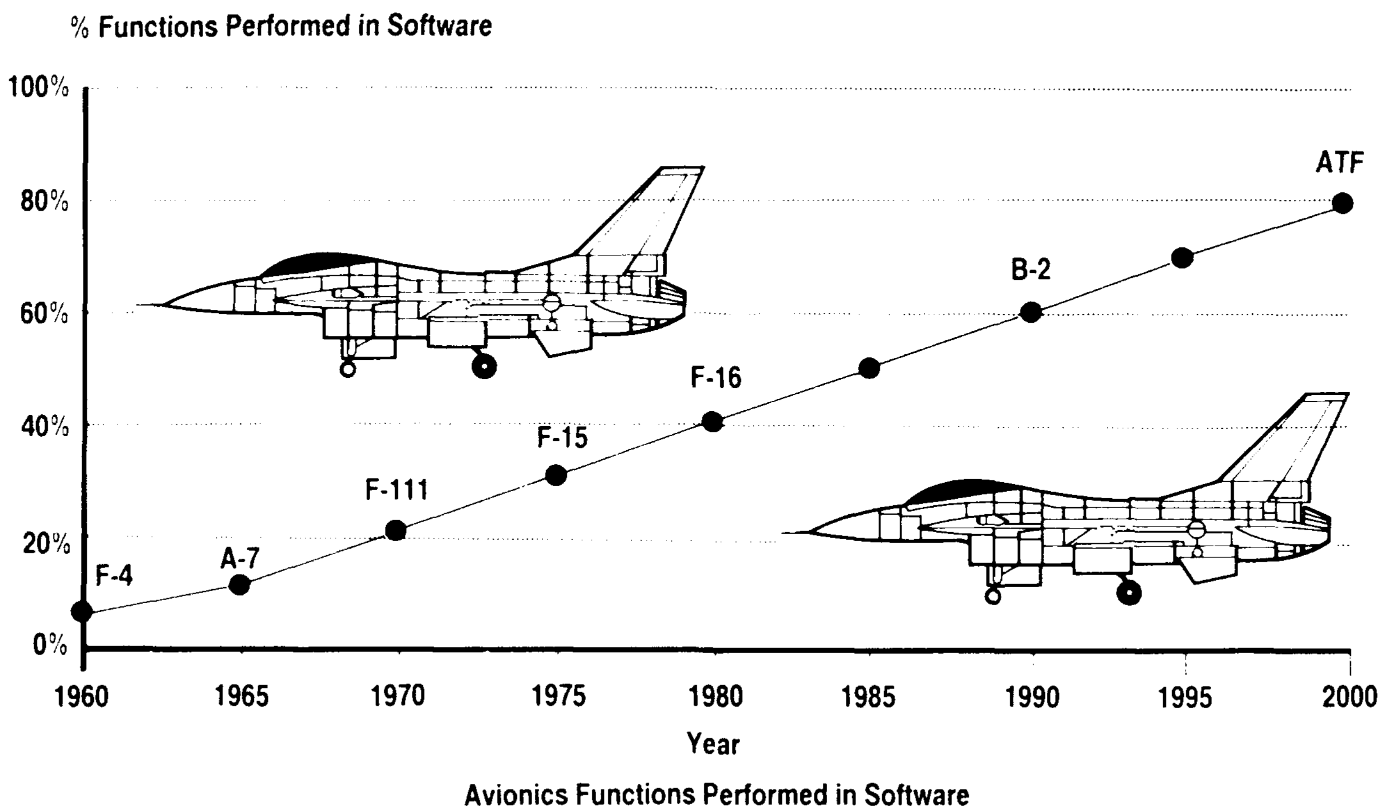


Figure 2. *Weapon system dependency: the growth of software.*

finally to automate error detection during its testing and validation. Since synchronization and timing errors in multi-process software are often transient and hard to reproduce, this application of specifications represents a technical breakthrough.

The TSL language is being developed further at Stanford University under AFOSR sponsorship, to be applied in other projects relevant to development of complex Air Force avionics. This is a necessary technology transfer step in bringing TSL into industrial practice.

Payoff

The first project is the DARPA CPL/CPS (Common Prototyping Language and System). Stanford is teamed with TRW to develop a prototyping system under the new DARPA initiative in Rapid Construction of Large Distributed Time-Critical Systems. This system will support construction of prototypes of entire avionics systems and their analysis. It will result in a high degree of automated planning of production-quality implementations, reuse of previous component systems, and reduction of costs. TSL is playing a fundamental role in defining the specification language and analysis tools for CPL.

In a second project, Verification and Validation of Advanced Avionics, Stanford is teamed with Lockheed's Software Technology Center to develop techniques and tools for applying a combination of statistical testing methods and runtime monitoring methods based on TSL formal specifications to test and verify advanced avionics.

Contributing Organizations and People

This research was performed by Professor David Luckham and colleagues at Stanford University. This effort is part of the software end systems subarea within the Directorate of Mathematical and Computer Sciences and is currently managed by Dr. Charles J. Holland.

Computation Based on the Cerebral Cortex

Achievement

Researchers at the University of California at Berkeley have developed a computational method that is fast, learns from examples, and that *could be used to* track multiple targets using simulated olfaction. The approach, based on simulating the olfactory system, is already used to inspect parts in manufacturing processes.

Background

Since the advent of computing during World War II, researchers have often consulted biology to find clues to building intelligent machines. The original von Neumann computer used logic gates inspired from the model of the neuron developed by McCulloch and Pitts. These models, however, did not provide a reasonable mechanism for learning from examples. Their speed was also hampered by the "von Neumann bottleneck." This is why computers in common use today require precise input information, ar⁻ᵈ they become very slow when their tasks become complex.

Recently, researchers have succeeded in creating systems that can learn from examples using networks of simple elements in parallel that mimic neurons. The parallel architectures also allow these systems to function at very high speeds. Many of these models, however, merely map a set of inputs to a set of outputs, and they do not perform complex sequences of actions.

The work of Drs. Freeman and Baird addresses the *learning of sequences* as being very similar to the olfaction. Olfaction is the process of sensing strong odors and then ignoring them so that successively weaker odors may be sensed.

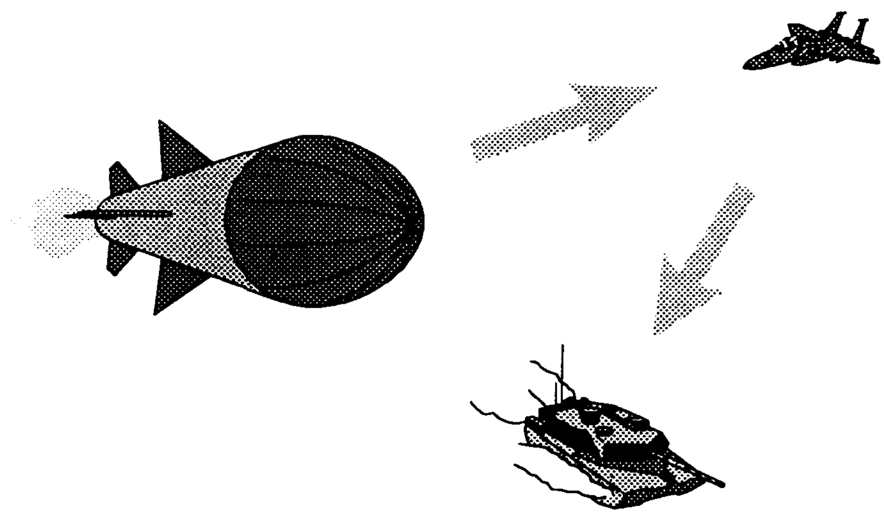


Figure 1. *Sample chaotic attractor stored by system.*

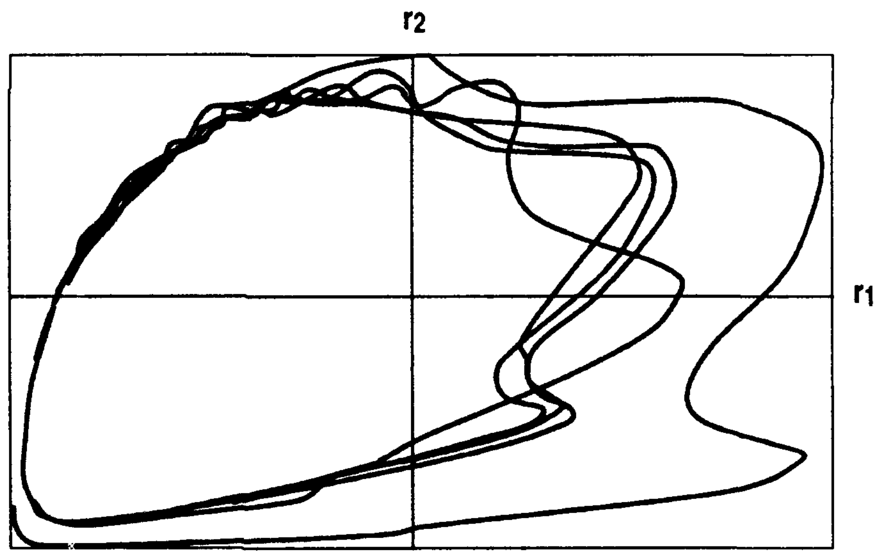


Figure 2. *Simulated olfaction can recognize targets in prioritized order.*

The researcher's various models are based upon the anatomy of the olfactory cortex. They consist of systems of coupled oscillators. The models can be programmed to store fixed data values as well as periodic and chaotic time series. The models closely emulate EEG readings taken from the rabbit olfactory system (figure 1).

Payoff

Dr. Freeman has demonstrated the ability of his system to solve real problems by using it to detect defects in machined metal parts on a conveyor. Although his

model is computationally simple, it outperforms all other known methods for detecting these defects with the exception of the close scrutiny of human experts. The simulated olfaction capability in the models of Drs. Freeman and Baird may one day be used to classify targets and threats in the order of their priority (figure 2). Thus, an in-flight warning system could be particularly sensitive to incoming missiles and yet maintain the capability to detect other targets such as tanks.

Contributing Organizations and People

Drs. Freeman and Baird are managed by Capt. Steven Suddarth of the Directorate of of the Directorate of Mathematical and Computer Sciences.